AllianceBernstein

Abating Climate Change

What Will Be Done and the Consequences for Investors

Research Conclusions

- Nuclear industry will boom
- Coal plants will be transformed
- Solar power, wind power and biofuels will disappoint expectations
- Plug-in hybrids will revolutionize road transport
- Advanced-battery and power-semiconductor markets will surge
- CO_2 sequestration, transportation and storage will create major new industries
- Oil industry will be at risk long term

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Research on Strategic Change
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About the Authors

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About Research on Strategic Change

Most fundamental research analysts cover an industry and the companies within it. AllianceBernstein's Research on Strategic Change group seeks to find investable ideas that stem from economic or technological changes powerful enough to profoundly influence corporate performance across multiple industries. **Abating Climate Change: What Will Be Done and the Consequences for Investors** is the group's fifth report. Prior publications include **Broadband: The Revolution Underway,** 2004; **China: Is the World Really Prepared?,** 2005; **The New Industrial Revolution: De-verticalization on a Global Scale,** 2005; and **The Emergence of Hybrid Vehicles: Ending Oil's Stranglehold on Transportation and the Economy**, 2006.

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A Special Note of Thanks

Hundreds of people have provided valuable information for this report, but Daniel Schrag deserves particular note. Dr. Schrag is a professor in the Laboratory for Geochemical Oceanography, Department of Earth and Planetary Sciences at Harvard University. We can't thank him enough for his intellectual generosity.

Executive Summary

We expect new regulations aimed at reducing greenhouse-gas emissions to have profound implications for many companies in a diverse set of industries. Even investors not convinced by the scientific case for man-made climate change can no longer afford to ignore the global push to contain greenhouse gases because it will affect trillions of dollars of investment flows over the next two decades.

A palpable change in public sentiment is spurring both voluntary and mandatory efforts around the world to reduce greenhouse-gas emissions. We expect such efforts to surge as governments pass increasingly strict regulations to combat what many perceive to be a real and growing threat to our planet's ecosystems and the well-being of millions of people.

We modeled the actions that carbon dioxide (CO_2) emitters would likely take to comply with the new rules at the lowest cost. We estimate that approximately US$5 trillion would be spent globally through 2030 by the owners of power plants and factories to reduce emissions of CO_2, the most pervasive greenhouse gas. Capital spending on power-related equipment would thus be twice as high as if nothing were done (*see display at left*). Billions more would fund efforts to improve the efficiency of energy-intensive equipment, such as automobiles, industrial motor systems and the motor systems required for various large consumer appliances, such as refrigerators and washing machines. (All our capital investment forecasts are in 2007 US dollars.)

These massive, yet manageable, investments could cause annual global emissions of CO_2 to fall below current levels by 2030 (*see display at right*). By then, atmospheric concentrations of CO_2 would be rising much more slowly than if nothing were done; by mid-century, atmospheric concentrations of CO_2 could start to decline.

Electric-power plants will be a primary focus of the new rules, because they are the largest and fastest-growing source of CO_2 emissions. Power plants now contribute about 36% of

Abatement Efforts Will Add Hugely to Global Power Capex
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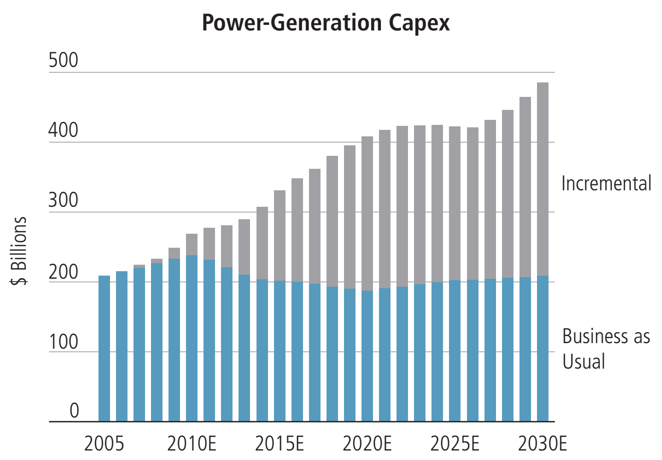

In constant 2007 dollars
Source: EIA, IEA and AllianceBernstein

Emissions-Control Efforts Could Make a Big Difference
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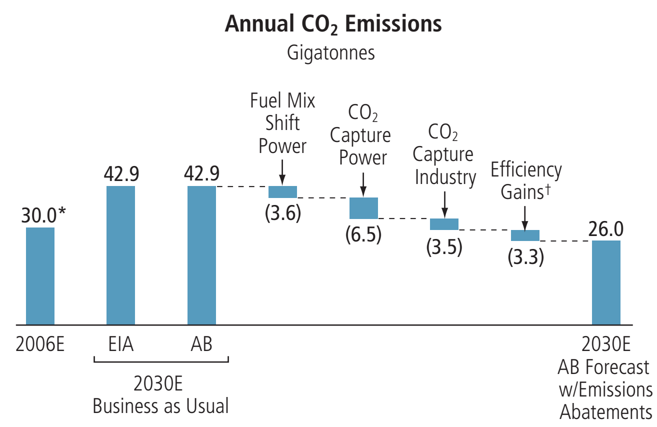

**Estimated from 2003 data*
†Includes impact of widespread adoption of hybrid vehicles
Source: EIA, IEA, Oak Ridge National Laboratory (ORNL), World Resources Institute (WRI) and AllianceBernstein

Power Generation Is the Largest Source of CO_2 Emissions

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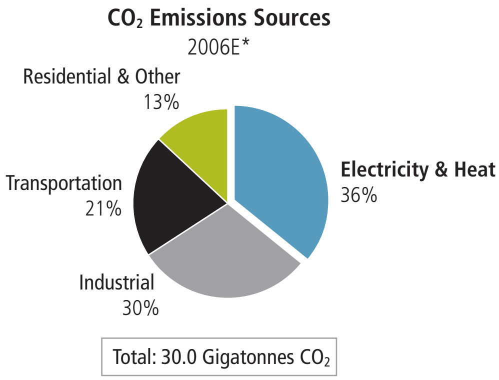

*Estimated from 2003 anchor data
Source: IEA, WRI and AllianceBernstein

total carbon dioxide emissions (*see display above*). Another 30% comes from industrial sources amenable to some of the same solutions.

We evaluated the five options for CO_2 emissions abatement on the basis of cost, political and technical obstacles, and impact on users. We eliminated one often-cited option—mandatory reductions of energy consumption—because its negative impact on the standard of living in both the developed and developing world would create insurmountable political obstacles. We eliminated another—increasing natural CO_2 absorption—because the approaches currently available are either too expensive or unworkable at the scale necessary to make a difference.

The remaining three options are expensive but feasible. Most importantly, they will all be pursued:

- *Improving energy efficiency* will be a significant element in reducing emissions, but its potential impact is finite.
- *Increasing power generation from sources that do not burn fossil fuels*, such as renewable and nuclear energy, will also be important.
- *Finding a way to capture and store CO_2 from fossil-fuel generation*, principally coal power, will be critical. Even with improved energy efficiency, increased power generation from nuclear and renewable sources will not provide enough electricity to meet global demand (*see display above right*). We conservatively forecast that demand for electricity will grow at 2.2% per year, from approximately 18 trillion kilowatt-hours today to almost 30 trillion kilowatt-hours in 2030. Our electricity demand forecast includes a reduction in demand due to significant efficiency gains in a wide range of applications, largely offset by an increase in demand due to widespread adoption of plug-in hybrid vehicles.

Nuclear and Renewable Energy Will Not Be Enough

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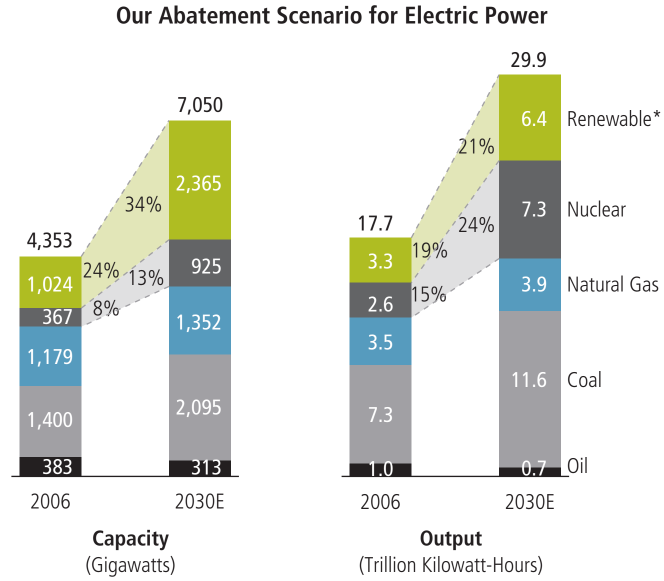

*Renewable energy includes hydroelectric, solar, wind, geothermal and biomass power.
Source: EIA, IEA and AllianceBernstein

Coal is cheap and abundant, and coal power is the most economical option when there is no cost for carbon emissions (*see display below*). Wind and solar power, in particular, are far more expensive.

But coal power emits more CO_2 per unit of electricity than the alternatives (*see display above on facing page*). Thus, cleaning up coal power is critical for reducing emissions. Many inefficient coal plants will be closed, and others will be retrofitted for carbon capture. New "clean" coal plants will be built as emerging technologies become more

At No Cost for CO_2, Coal Is Most Economical Option

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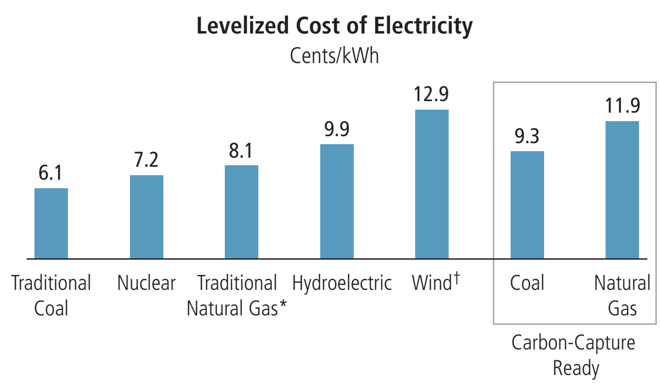

For solar power, levelized cost is 58.2 cents per kilowatt-hour.
Assumes natural gas costs $8 per million BTUs
†*Excludes cost to integrate intermittent power into electric grid and cost of backup power*
Source: IEA and AllianceBernstein

cost-efficient. By 2030, only about 30% of the world's coal-power plants will release CO_2 into the atmosphere at a rate comparable with today's facilities. We forecast that global capital investment in coal power will more than double before 2025 from about $90 billion per year today, with the biggest surge coming between 2015 and 2020. We expect this massive capital spending to increase coal-power capacity by about 50% by 2030. Coal power's dominant share of total electricity generated will remain virtually unchanged at 39%, compared with 41% today.

Capturing, compressing and transporting CO_2 from coal and natural-gas power plants, as well as some factories, will create new industries. It will also create value from nearly worthless properties, such as depleted oil and gas fields, which are geologically suitable for CO_2 storage. Our research suggests that the global daily volume of CO_2 captured and sequestered will exceed 7 billion cubic feet (bcf) a day by 2010, approach 70 bcf by 2020 and hit 500 bcf a day before 2030—roughly double the amount of natural gas currently flowing through pipelines worldwide on a daily basis. This would create an opportunity for pipeline operators and owners.

Some oil-field service firms will also benefit from a new market opportunity in CO_2 injection. We expect annual spending on injection and storage of CO_2 to reach $1 billion by 2015, hit $9 billion by 2020 and leap to $80 billion by 2030. The technology exists: Oil-field service firms already use CO_2 injection to increase production from partially depleted fields.

Nuclear energy is emerging as the new green power source. Now improved in a variety of ways, nuclear power is beginning to regain public acceptance in the US and Europe. As carbon constraints boost electricity prices from other sources, nuclear power will become the lowest-cost source of electricity (*see display at right*). We forecast that nuclear-power capacity will nearly triple by 2030. By 2020, this build-out will lead to a 10-fold increase in the market for nuclear-power equipment.

Renewable energy is *not* the cure for the world's addiction to fossil fuels. Wind, solar and hydroelectric power all have compelling advantages, such as an inexhaustible fuel supply and minimal emissions of CO_2. But wind and solar power also have severe disadvantages, including cost, reliability and transmission problems. Hydroelectric power does not face the same obstacles but is only available in limited locations.

We expect policy-driven investment in wind and solar power to be massive, with combined capacity increasing from less than 80 gigawatts today to almost 900 gigawatts by 2030. However, the overall increase in electricity production from these sources will be significantly less than the increase in capacity because of their low utilization rates. Furthermore, the high costs of wind and solar power will make widespread deployment uneconomic for the foreseeable future, as the bottom display on the facing page also shows.

A push for greater energy efficiency in a wide range of applications will also help reduce energy demand and, therefore, CO_2 emissions. This will create attractive investment opportunities in some makers of electronic components for industrial motor systems, home appliances and cars. Indeed, it will help transform the auto industry: Carbon-emissions regulations will speed the adoption of hybrid vehicles and, later, plug-in hybrid vehicles.

The Problem with Coal: High CO_2 Emissions

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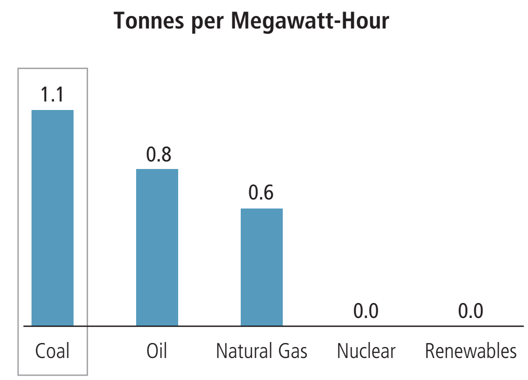

Source: IEA and AllianceBernstein

If There's a Cost for CO_2 Emissions, Nuclear Is Cheapest

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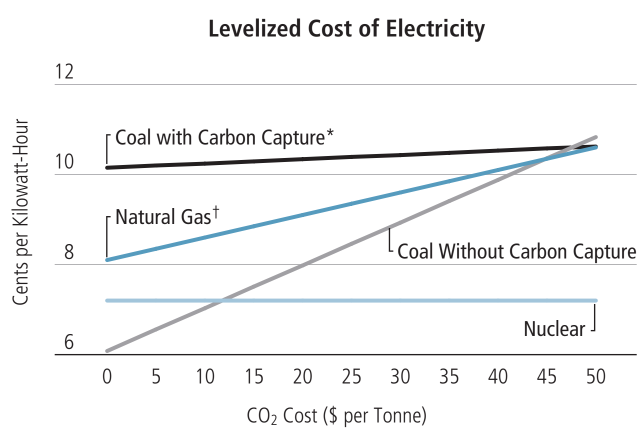

*Includes cost to transport and store CO_2
†Assumes natural gas costs $8 per million BTUs; without carbon capture
Source: IEA and AllianceBernstein

We estimate that the number of hybrid or plug-in hybrid light-duty vehicles on the road globally will near 1 billion by 2030, dwarfing the 365 million conventional cars (*see display at right*). We expect the incremental electricity demand from plug-in cars and pickup trucks to increase projected electricity demand in 2030 by about 7%. It would also, however, reduce oil demand from these vehicles by 50%, and thus reduce total global oil demand by over 13%. The result would be a net decline of 39% in CO_2 emissions from light-duty vehicles. We also expect trucks and buses to be hybridized. The eventual adoption of plug-in hybrid technology for trucks and buses would further reduce oil demand and increase electricity demand.

Automotive batteries and battery-management systems may be the product category that benefits most from the changes that we expect. Currently, the annual automotive battery market is about $9 billion and consists mainly of lead acid batteries. As new, more powerful lithium-based batteries are introduced, we expect the market to grow to over $150 billion.

Oil producers and refiners will be among the biggest losers. Adoption of plug-in hybrid vehicles is likely to cut demand for gasoline and diesel at the same time that CO_2 flooding of mature oil fields increases oil production. In the medium to long term, the confluence of lower demand and increased supply will be troublesome for the industry. In the near term, neither factor will be large enough to change the sector's dynamics.

Consumers of electricity will also be adversely affected by the developments that we expect. For most people, however, electricity represents a fairly small percentage of disposable income. Although electricity costs will rise faster than costs generally, the overall impact will likely be relatively minor for most individuals, and it may be ameliorated somewhat by the adoption of more efficient electric devices and building systems, as well as progressive electricity-pricing schemes. However, companies that consume a great deal of electricity, such as cement and aluminum manufacturers, will be hurt, unless they can reduce their power consumption or find cheaper sources of electricity by relocating.

The efforts that we describe will cost trillions of dollars over the next two decades, but we believe that they are manageable and that they may stimulate economic growth in many regions. Abatement efforts will create many relatively high-paying jobs as new nuclear and clean-coal facilities are constructed and transmission lines are built to connect renewable resources to electric grids around the world. As electricity prices rise globally, companies will relocate to take advantage of relatively cheap power in areas that either develop low-cost nuclear facilities or capitalize on natural hydropower or geothermal resources.

If climate scientists are correct, the earth will continue to warm despite the aggressive emissions-abatement scenario that we outline. However, the earth would warm less than if nothing were done, and the consequences would be adverse, rather than catastrophic. Still, adapting to changes in sea levels, weather and water availability will likely impose significant social and economic costs. ■

Adoption of Hybrid Vehicles Could Also Reduce CO_2 Emissions

(Display 83, page 80)

2030E	AB Emissions-Abatement Case			IEA/SMP* Reference Case
	Hybrids	Non-Hybrids	Total	Total
Light-Duty Vehicle Stock (Millions)	924	365	1,289	1,289
Miles Driven per Year	11,150	5,592	9,576	9,576
Miles per Gallon	62.2	25.1	50.0	25.1
Annual Oil Use (Billions of Gallons)	165.6	81.3	247.0	491.8
Incremental Electricity Demand (Trillions of Kilowatt-Hours)	1.9	0	1.9	0
CO_2 Emissions (Gigatonnes)				
– from Oil	1.5	0.7	2.3	4.5
– from Electricity	0.4	0	0.4	0
– Total	1.9	0.7	**2.7**	**4.5**

**Assumes hybrids achieve 50% driving from plugging into the electric grid and carbon intensity of power generation is 0.21 tonnes per megawatt-hour. In its reference case, the IEA assumes hybrids will account for less than 1% of the light-duty vehicle stock by 2030 and have an average mpg of 35. We adjusted the mileage assumptions in the IEA/SMP model to reflect subsequent disclosures from IEA staff.*

Source: IEA/SMP and AllianceBernstein

Abating Climate Change

What Will Be Done and the Consequences for Investors

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INTRODUCTION

Perhaps it was the affecting pictures of polar bears stranded on ice floes as the Arctic ice sheet melted. More likely, it was the widespread publicity surrounding a host of high-profile reports on climate change,[1] coupled with an unusually large number of extreme droughts and violent storms in various parts of the world. Whatever the reason, there has been palpable change in public sentiment about the need to reduce greenhouse-gas emissions—particularly in the US and Australia, the only two developed countries that until recently had not endorsed and sought to comply with the Kyoto Protocol on Climate Change.

In April 2007, a *New York Times*/CBS News poll found that "[s]ome 84% of Americans think that human beings are contributing to global warming, with 78% saying that we should do something about it 'right away.' " In drought-ridden Australia, a September 2007 World Public Opinion poll found that over 90% of the population agreed that action must be taken to mitigate climate change, and over two-thirds said that it constitutes a "critical threat" and must be immediately addressed "even if this involves significant costs." In December, Australia's newly elected prime minister, Kevin Rudd, ratified the Kyoto Protocol.

To us as investment analysts focused on identifying broad trends that could have transformative investment implications across a wide range of industries, this gradual shift in public sentiment was crucial. Although four years ago we had decided against doing a comprehensive research study of the investment implications of climate change, two years ago we reversed that decision. Why? We had begun to see a much greater likelihood of an aggressive, global effort to reduce man-made emissions of greenhouse gases—an effort that could have dramatic impact on many industries. Developments since we began our study have only deepened our confidence that widespread, comprehensive greenhouse-gas regulation is coming.

Not Our Debate

Of course, there's still debate about the scientific case that man-made emissions of greenhouse gases will lead to significant changes in average global temperatures that could eventually have catastrophic consequences. Scientists point to the shrinking of long-stable equatorial mountain glaciers and of the Arctic Sea's summer ice sheet (*Display 1, next page*) as visible proofs of man-made climate change. Critics point out, correctly, that climate science is not precise: The complex interactions between melting glaciers and ice floes and their impact on ocean currents and weather patterns, for example, remain extremely difficult to model.[2] Perhaps, they say, any change in global temperatures is because of natural variability.

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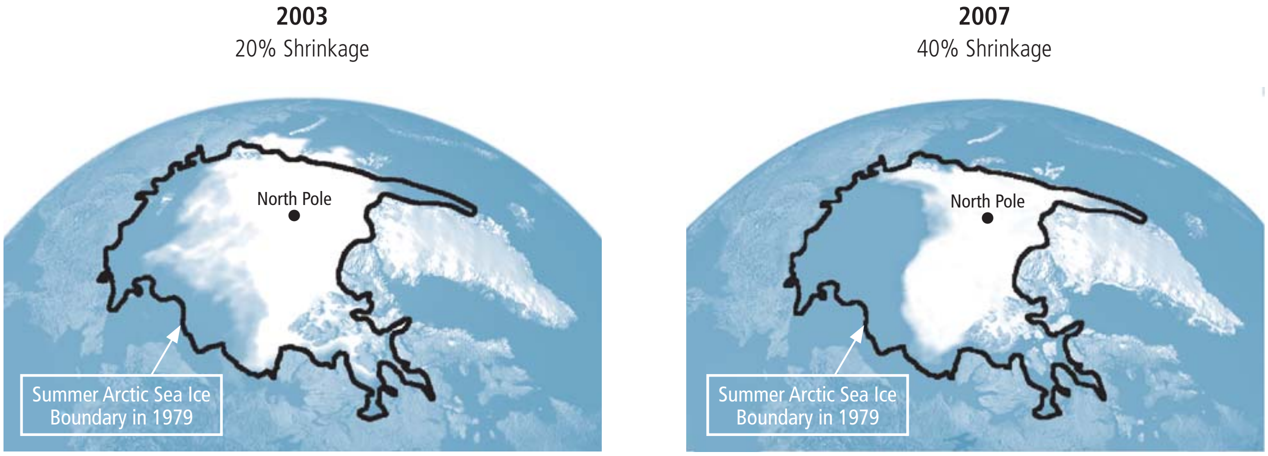
1 The two most important of these reports, in terms of impact, were probably the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) and *The Economics of Climate Change: The Stern Review*, both published in 2007. In addition, *An Inconvenient Truth,* the documentary film about former US Vice President Al Gore's campaign to stop man-made climate change, appears to have had a decided political impact.

2 Geochemist Daniel Schrag responds that the science is imprecise because it takes mankind into uncharted territory. "Mankind is entering on a global ecological experiment that has never before been tried," Schrag says. "Thus, the outcomes cannot be predicted with confidence." One can, however, act to forestall a possible, or even probable, disaster—just as one pays to fireproof one's house and purchases fire insurance, without knowing if a fire will ever break out.

Display 1

The Arctic's Summer Ice Sheet Is Shrinking



Source: Natural Resources Defense Council and NASA

While we briefly outline the science of climate change in this report, the scientific details and their validity (or lack thereof) are largely irrelevant to our analysis. Whether man-made global warming is fiction or fact, the world is poised to make colossal investments in electric-power infrastructure and other technologies to slow the accumulation of greenhouse gases in the atmosphere.

The question is not *if* or *when* action will be taken, but *what* will be done. After two years of intensive research, including over 500 visits and interviews with companies, consultants, scientists and legislators, we predict that the effort to reduce greenhouse-gas emissions will require trillions of dollars of capital, take decades to complete and have profound implications for the addressable market and potential growth rate of hundreds of corporations around the world. Thus, it merits intense study by investors.

What Will Be Done

In this report, we model a fairly comprehensive set of efforts to significantly reduce emissions of carbon dioxide (CO_2), the main man-made greenhouse gas. These efforts will be expensive, costing an estimated US$5 trillion in aggregate by 2030 just to reduce the CO_2 emissions from stationary sources. Nonetheless, we believe the cost is manageable financially: Our model projects incremental spending related to mitigating climate change (including expenses related to carbon capture and storage) rising to approximately $500 billion in 2030. This number, while certainly large, represents less than 2% of forecasted global capital spending in the same year. As a further point of comparison, in 2006 global military spending exceeded $1 trillion.[3]

These massive, but feasible, investments could have a significant impact on greenhouse-gas emissions and atmospheric concentrations. Under our model, annual emissions would begin to decline in 2015. Atmospheric concentrations would continue to rise throughout our forecast period (through 2030), but at a much slower rate than if nothing were done. This slower rate would allow mankind more time to relocate population centers and adjust agricultural production if, as scientists predict, rising atmospheric concentrations of greenhouse gases lead to climate change.

The technologies that we predict will be deployed to meet these goals are either commercially available today or in very advanced stages of trials and testing. They will improve over time. Perhaps other, not yet imagined, innovations will help to reduce atmospheric concentrations of greenhouse gases even more rapidly: Sir Richard Branson has offered a $25 million prize to anyone who devises a way to remove 1 billion tonnes of CO_2 from the atmosphere. We do not, however, assume such breakthroughs in our model.

We also do not assume a massive rollback in global consumption or global growth as people—voluntarily or by edict—adopt new, so-called green lifestyles. We do assume, however, that regulation and price incentives of various kinds—from carbon caps and taxation to higher electricity prices—will result in a shift to more efficient technologies and perhaps behavior and lifestyle changes that reflect the higher cost of using fossil fuels.

[3] *Stockholm International Peace Research Institute Yearbook 2006*

Our Forecasts

Today, there are only a few ways to reduce greenhouse-gas emissions without impeding global growth. We assume that *all* of them will be deployed to some degree. We have used our research-based judgment of costs, feasibility and political support to determine the extent to which each tool will be used.

We predict that the biggest beneficiaries of the effort to forestall climate change will be makers of power-generating equipment and electric-transmission equipment. The single biggest product category to gain may be automotive batteries, which will go from a $9 billion market today to a market with annual revenues of well over $150 billion by 2030, as concerns about climate change accelerate the adoption of hybrid vehicles and eventually of plug-in hybrids. Makers of hybrid vehicles, power semiconductors, and advanced motors and drives will also be big gainers, along with pipeline operators, some oil-field service providers, and construction and engineering firms.

Consumers of electricity—both households and industries—will also be hurt by rising electricity prices. For cement and aluminum manufacturers, for example, it may not be easy to pass through the higher input cost of electricity. Hence, their margins may be squeezed. To remain competitive, these industries will need to either devise less energy-intensive production processes or locate production in countries or regions with relatively cheap electricity, perhaps from sources such as hydroelectric or geothermal plants.

Long term, oil producers and refiners will also be quite vulnerable to the impact of emissions-abatement efforts. Electrification of road transport will significantly reduce demand for gasoline and diesel fuels, while oil supplies may grow meaningfully as a result of enhanced oil-recovery efforts that boost the output of mature oil fields by flooding them with CO_2.

Electric utilities will fall in the middle. Those utilities with low-cost, low-carbon-emitting generating plants, such as hydroelectric plants and nuclear plants, will likely enjoy strong earnings growth. Those with large sunk costs in facilities with high carbon emissions may be hurt, depending on the regulatory scheme adopted.

Of course, our predictions will not be accurate in detail: Projections over 20 years will always be off to some degree and fail to foresee some developments that eventually arise. Nonetheless, we believe that our predictions of the technologies that will be deployed and the policies that will be adopted will be directionally correct, even if adjustments are later required.

Some of the developments we foresee are already under way; others are less mature. Many company managements we interviewed, for example, said they are reluctant to invest in carbon-reducing technologies until they know what the new rules will be. "Why should I invest millions of dollars to retrofit my coal plants if their emissions will be allowed under a 'grandfather' clause in new regulations adopted in a couple of years?" they ask. "I can't make capital decisions on equipment that will last for 40 to 60 years without some certainty about how much I'll have to reduce emissions." Thus, our model assumes that some new technologies will not be adopted until regulatory requirements become clear.

Investors may also be tempted to wait until these developments are more mature. We think that would be a mistake. While the trillions of dollars that we expect will be spent on mitigating climate change will be disbursed over decades, the market routinely discounts long-term cash flows in pricing equities. Investors who hold off too long may miss large opportunities to profit from investments in companies benefiting from the developments that we foresee—and may invest in other companies that will be hurt. We are working with our firm's industry analysts and portfolio managers to take these trends into account as they evaluate potential investments. ■

THE SCIENCE OF CLIMATE CHANGE

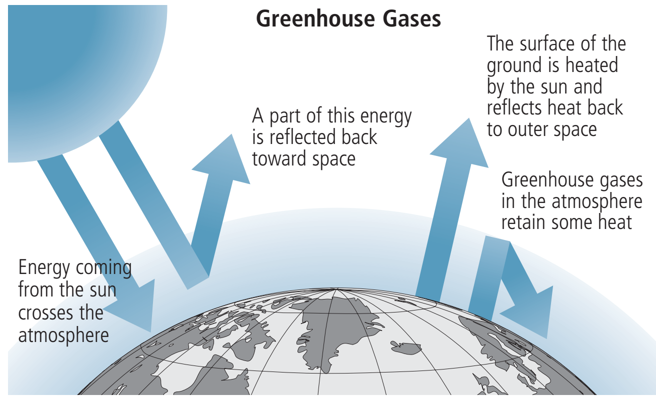
According to the greenhouse theory, the Earth's troposphere—the lowest portion of the atmosphere—is integral to maintaining the Earth's temperature balance. The troposphere, which contains 80% of the atmosphere's mass, is where so-called greenhouse gases accumulate. Like a huge thermal blanket, these gases trap the sun's radiation (the principal source of warmth on Earth), enabling the Earth to maintain a temperature favorable for life (*Display 2*). Without this shield, the Earth's average temperature would be about 60°F (33°C) colder,[4] and Earth would be uninhabitable. The greenhouse effect is what makes life as we know it possible.

But there can be too much of a good thing. Too much greenhouse gas makes life on Venus impossible (see "The View from Venus," page 10) and, climate scientists say, may disrupt life on Earth. The core argument for man-made global warming is that prior to the Industrial Revolution there were 2,210 billion tonnes (2,210 gigatonnes)[5] of CO_2 in the atmosphere. Since 1850, however, human activity has increased total CO_2 in the atmosphere to almost 3,000 gigatonnes,[6] and because of our current energy infrastructure, every year we are adding more.

The primary way that people generate energy—and carbon emissions—is by burning fossil fuels.[7] In 2006, people generated roughly 30 gigatonnes of CO_2 emissions. The earth and oceans absorbed roughly 12 gigatonnes, so CO_2 in the atmosphere increased by roughly 18 gigatonnes (*Display 3*). We estimate that if no action is taken to curtail emissions, another 522 gigatonnes (892 emitted less 370 absorbed) would accumulate in the atmosphere by 2030. Almost 3,500 gigatonnes of carbon dioxide would then be in the atmosphere, almost 40% of it attributable to human action. By 2030, mankind would still be adding 24

Display 2

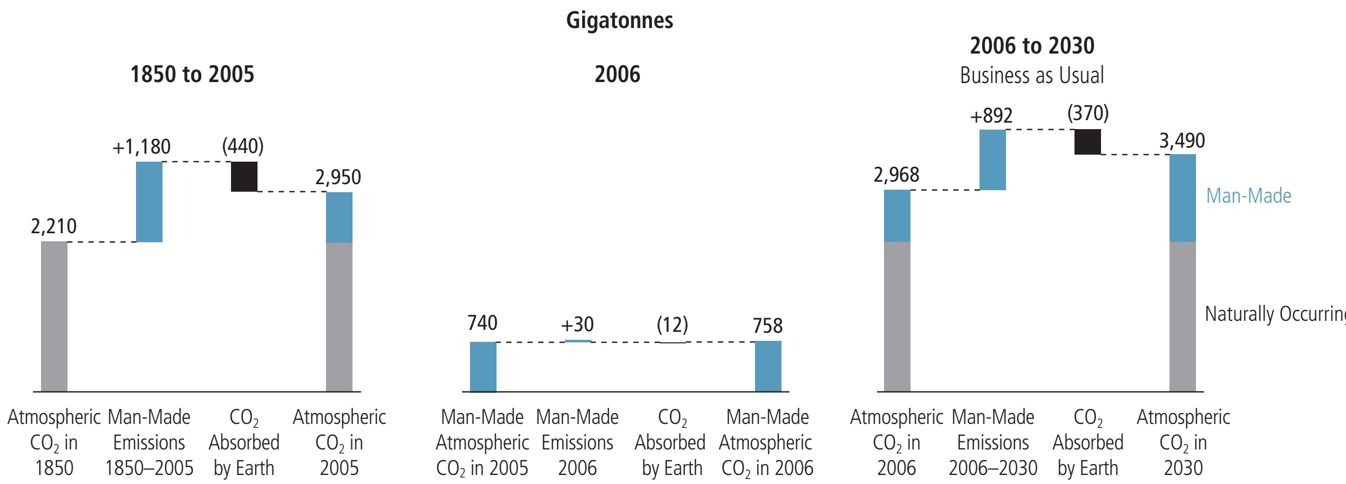
Greenhouse Gases Trap the Sun's Radiant Energy



Source: Isover

Display 3

CO_2 Emissions Outpace the Earth's Capacity to Absorb Them



4 IPCC, fourth assessment report

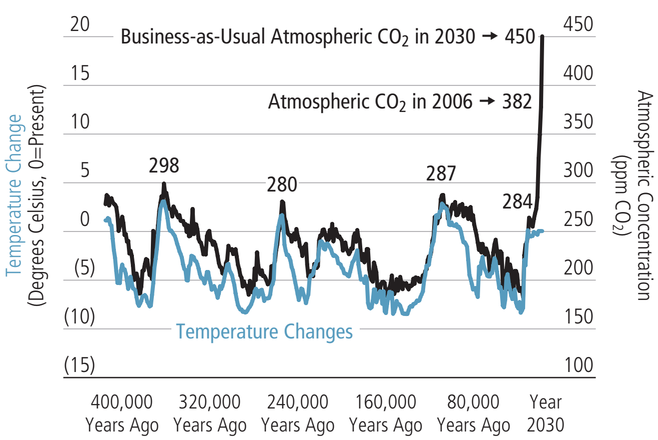
5 One gigatonne equals 1 billion tonnes; one megatonne equals 1 million tonnes.

6 380 parts per million of CO_2 equal 2,950 gigatonnes of CO_2.

7 Fossil fuels accounted for over 85% of global energy use in 2003, according to the International Energy Agency (IEA) *World Energy Outlook*, 2006.

Display 4

Temperature Has Fluctuated with Atmospheric CO_2



Source: Arctic and Antarctic Research Institute, Laboratoire de Glaciologie et de Géophysique de l'Environnement and Laboratoire des Sciences du Climat et de l'Environnement and AllianceBernstein

gigatonnes (net) of CO_2 to the atmosphere a year. The net addition would keep rising thereafter.

Any changes to the climate that we may be observing now, climate scientists say, can primarily be attributed to the 758 gigatonnes of CO_2 that people have added to the atmosphere since 1850. Continued increases in atmospheric CO_2 will increase average global temperatures further: The correlation between atmospheric CO_2 and global temperature is very close (*Display 4*).

Carbon Matters Most

There are actually several greenhouse gases, each with a distinct propensity to trap heat and distinct atmospheric life span (*Display 5*). Water vapor is by far the most abundant greenhouse gas, constituting up to 4% of the atmosphere's volume. It also plays a crucial role in the climate system, with low thick clouds reflecting much of the sun's heat back into space while high thin clouds allow the sunlight through and trap the heat inside. Human activity does not directly influence the amount of water vapor in the atmosphere.

In this report, we, like most climate scientists, focus on CO_2, the second most abundant greenhouse gas after water vapor. While CO_2 constitutes less than 0.04% of the Earth's atmosphere today, it accounts for 74% of mankind's yearly contribution to atmospheric greenhouse gases (*Display 6, next page*). Other gases are also significant. Most notably, methane (CH_4) and nitrous oxide (N_2O) are more effective at trapping heat than CO_2, but methane doesn't remain in the atmosphere nearly as long. Also, both methane and nitrous oxide are emitted in such small quantities relative to CO_2 that their overall impact is fairly low: For every 10,000 molecules of CO_2 emitted as a result of human activity in 2006, 260 methane molecules and four nitrous oxide molecules were emitted.[8] In addition, CO_2 emissions are growing much faster than emissions of other man-made greenhouse gases.

Display 5

The Global Warming Potential for Select Greenhouse Gases Varies Widely

Greenhouse Gas	Atmospheric Lifetime (Years)	Global Warming Potential Relative to CO_2 over 100 Years	2006E Quantity Emitted*	
			Tonnes (Millions)	CO_2 Equivalents† (Billions)
Carbon Dioxide (CO_2)	50–200	1	30,000	30.0
Methane (CH_4)	12	23	280	6.5
Nitrous Oxide (N_2O)	114	296	12	3.4
Sulfur Hexafluoride (SF_6)	3,200	22,200	0.002	0.050
Trifluoromethane HFC-23 (CHF_3)	260	12,000	0.012	0.110
Perfluoromethane (CF_4)	50,000	5,700	0.150	0.720

**Estimated from 2000 anchor data*

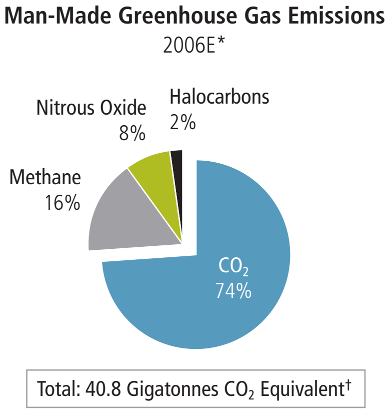
†*Non-CO_2 emissions are expressed in CO_2 equivalents using 100-year global warming potentials found in the IPCC's third assessment report.*

Source: IPCC, World Resources Institute (WRI) and AllianceBernstein

8 CO_2 and N_2O both have a molecular weight of 44.01 grams, while NH_4 has a molecular weight of 16.04 grams. Thus, one tonne of NH_4 contains 2.75 times as many molecules as one tonne of CO_2 or N_2O.

Display 6

CO_2 Emissions Are Largest Contributor to Greenhouse Effect



**Estimated from 2000 anchor data*

†Non-CO_2 emissions are expressed in CO_2 equivalents using 100-year global warming potentials found in the IPCC third assessment report.

Source: International Energy Agency (IEA), IPCC, WRI and AllianceBernstein

The Carbon Cycle

Carbon is a basic building block of life. Plants feed themselves by creating carbohydrates from CO_2, water and light in the process called photosynthesis. Thus, plants take CO_2 out of the atmosphere. Animals breathe, taking in oxygen and returning CO_2 to the atmosphere. Microbes and bacteria consume CO_2 and return oxygen to the air, and break down organic materials, releasing greenhouse gases such as nitrous oxide and methane into the air, soil or oceans. The land and ocean also act as natural carbon "sinks," absorbing atmospheric carbon. Over millions of years, carbon-rich organic materials have been buried in the earth and transformed under pressure into oil, natural gas and coal.

There is a natural balance in the carbon cycle, with seasonal fluctuations: More carbon is naturally absorbed in summer when the trees and plants are active than in winter when they are dormant. Because the majority of the Earth's land area is in the Northern Hemisphere, the Earth tends to absorb more CO_2 from June through September than it does from December through March.

Changes in the Earth's axis and rotation around the sun, solar activity (which can change the energy flow from the sun to the Earth), tectonic plate movements and volcanoes can also change the climate and cause shifts in the Earth's natural carbon balance. Thus, there are the long periods known as glacial maxima, when the poles and much of the Eurasian and North American continents are covered in ice, as well as interglacial warm periods.

Scientific analysis of the CO_2 content of deep ice cores shows that the concentration of CO_2 in the atmosphere has varied over the past 650,000 years from about 180 parts per million (ppm) during the glacial maxima to roughly 290 ppm during the warmer periods. Clearly, atmospheric CO_2 and average global temperatures are very closely correlated.

Technically, the Earth is still in an Ice Age, because the North and South Poles and high mountain peaks are glaciated, but average temperatures are far warmer than in the last glacial maximus, which ended about 12,000 years ago. For most of the last 12,000 years, atmospheric CO_2 concentrations have hovered around 260 ppm. In about 1850, it was 284 ppm; since then, atmospheric CO_2 concentrations have risen sharply—to 320 ppm by 1960 and to more than 380 today (*Display 7*). Given the established infrastructure and continued global economic growth, CO_2 emissions will continue to accelerate over at least the short to medium term. We expect atmospheric CO_2 to reach 430–50 ppm by 2030, depending on how aggressively humanity acts to curb emissions.

The Human Impact

Most climate scientists believe mankind has disrupted the natural carbon cycle and climate balance in a few ways. Most important, burning fossil fuels—particularly coal, oil and natural gas—releases carbon into the atmosphere that had been locked deep beneath the ground or sea for millions of years. Hence, the rapid increase in

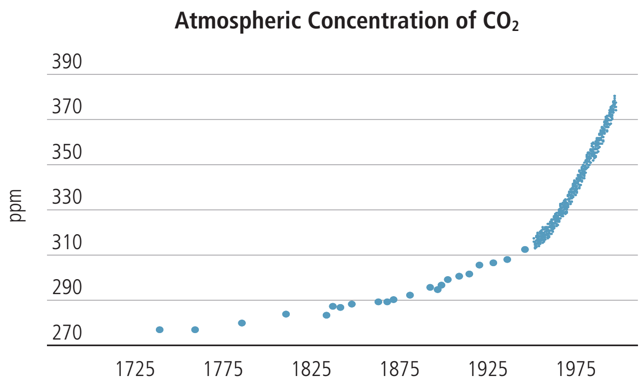
THE VIEW FROM VENUS

How powerfully can greenhouse gases influence temperatures? Just look at Venus, sometimes called Earth's "sister planet." The two planets are similar in size, gravity, material composition and distance from the sun. They also have similar concentrations of CO_2.

On Earth, however, most of the CO_2 is buried underground. On Venus, it has been exhumed by volcanic activity. The result: Venus' atmosphere is 98% CO_2, and its average surface temperature is 891°F. By comparison, Earth's atmosphere is 78% nitrogen, 21% oxygen and only 0.4% CO_2. Its average surface temperature is 59°F. ■

Display 7

CO_2 Buildup Has Accelerated in Recent Years



Source: Physics Institute, University of Bern and Scripps Institution of Oceanography

carbon emissions closely parallels growth in burning of fossil fuels for heat, transportation and electricity generation over the past 200 years.

Second, human beings have disrupted carbon absorption. The oceans do the bulk of the heavy lifting in the natural carbon cycle, sequestering almost 10 gigatonnes of human-emitted CO_2 per year.[9] There is a natural balance between the carbon dioxide in the atmosphere and the carbon dioxide in the ocean. As people release more CO_2 into the atmosphere, more CO_2 dissolves into the ocean to restore this balance. Some of the CO_2 dissolved into the ocean is used by photosynthesizing phytoplankton and becomes part of the organic carbon cycle. But as more and more CO_2 dissolves into the ocean, the ocean tends to become more acidic. Ultimately, this could prove disruptive to the phytoplankton that would otherwise process the dissolved CO_2.

Based on the most recent scientific data, we estimate that about two gigatonnes of CO_2 are naturally absorbed by land every year,[10] but that may change with land-use practices. Deforestation and desertification—largely the result of farming and development activity—tend to decrease carbon uptake. At the same time, warmer temperatures tend to increase the soil respiration of microbes, leading to the quicker return of CO_2 into the atmosphere. Somewhat offsetting these factors, increased CO_2 concentrations also facilitate faster plant growth, which boosts plant consumption of CO_2.

While the interactions are complex, the scientific consensus is that human action is changing the natural carbon and temperature balance: Current activity appears to be leading to far greater CO_2 emissions than the land and oceans are able to absorb. Over the past 40 years, roughly 40% of the carbon dioxide emitted has been absorbed by land and sea. We expect that trend to continue in the near term, but it is not clear that Earth will be able to continue absorbing CO_2 at a similar rate over the long term.

How Much Is Too Much?

Studies of feedback effects take into account the interaction of two or more variables, which can lead to very different results from those achieved by studying any one variable alone. For climate-change studies, there are several feedback effects with dramatic consequences, including the impact of warmer temperatures on soil respiration mentioned above. In addition, a warmer ocean can absorb less CO_2. Warmer temperatures would also likely cause a dieback of the Amazon rainforest, which would reduce carbon storage in plants. If the Arctic or Antarctic permafrost thaws, underground methane would be released into the atmosphere.

In 2006, the Hadley Centre published its analysis of likely changes to the carbon cycle as the cycle adjusts to elevated temperatures and atmospheric concentrations of CO_2.[11] The Centre found that by 2050, Earth's ability to absorb fossil-fuel emissions could be degraded by 21%–33%.

How much this matters is an ongoing debate. However, scientists point out that average global temperatures fluctuate within a very narrow range. They were only about 5°C lower in the last glacial maximum, when bitter cold contributed to massive extinctions of plant and animal life. They were only 3°C higher the last time the North and South Poles were free of ice, when palm trees grew in Wyoming and northern China, crocodiles swam in the Arctic Ocean and pine forests covered Antarctica.

Over the past 150 years, average global temperatures have risen by 0.8ºC; they have risen by 0.5ºC in the past 30 years[12] (*Display 8, next page*). Though that may sound like a small amount, it has affected the Earth unevenly: Alaska and Siberia have experienced an average surface

[9] We estimate that the ocean absorbed 9.9 gigatonnes of CO_2 in 2006. This figure is derived from "Inverse Estimates of Anthropogenic CO_2 Uptake, Transport, and Storage by the Ocean," S.E.M. Fletcher et al., *Global Biogeochemical Cycles*, 20 (2006), which suggests that the ocean absorbed 8.1 gigatonnes of CO_2 in 1996. In the short term, higher atmospheric concentrations should lead to higher levels of ocean absorption.

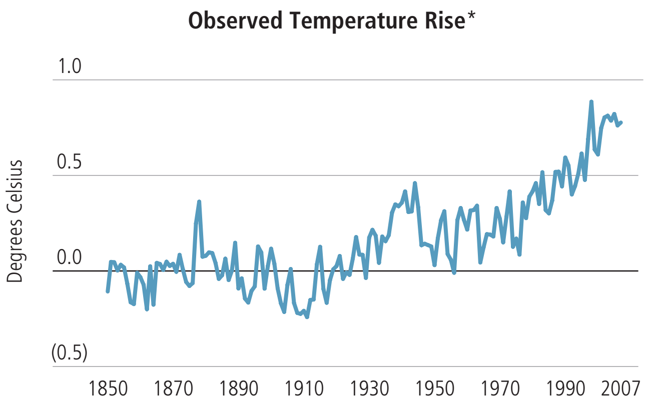
[10] Estimates vary widely; for more information, see Appendix B, Our CO_2-Emissions Model.

[11] Chris Jones et al., "Impact of Climate-Carbon Cycle Feedbacks on Emissions Scenarios to Achieve Stabilisation" (2006)

[12] Temperature change over the last 150 years is relative to average global temperatures from 1850 to 1900; temperature change over the last 30 years is relative to average temperatures from 1974 to 1980.

Display 8

The World Is Warming



**Average yearly surface temperature measured against baseline of 1850–1900 average*
Source: N.A. Rayner, et al., 2003: Globally complete analyses of sea surface temperature, sea ice and night marine air temperature, 1871–2000. J. Geophysical Research 108, 4407 and P.D. Jones, et al., 1999: Surface air temperature and its variations over the last 150 years. Reviews of Geophysics 37, 173–199

temperature increase of 2°–3°C. Even that relatively small amount has been enough to cause the visible reductions in the Arctic's summer sea ice, mountain snowcaps and Greenland's ice sheet. Nonetheless, it's far *less* than the spike in atmospheric CO_2 might lead one to expect.

The Earth's climate is a large and complex system that takes a long time to equilibrate after being disturbed by events such as the injection of 1,210 gigatonnes[13] of CO_2 into the atmosphere since 1850. Climate models indicate that even if atmospheric concentrations of CO_2 were to stabilize at current levels, global temperatures would continue to rise.

But it will not be possible to stabilize atmospheric concentrations at current levels, because it would be impossible to reduce emissions enough overnight. The world simply cannot change all its power plants, factories, heating and cooling systems, appliances and transportation systems at once. Indeed, our model shows that it would take a concerted effort across all major economic sectors and regions of the world to stabilize atmospheric concentrations below 450 ppm by 2050 and to significantly reduce atmospheric concentrations thereafter.

Even with the large-scale global effort we have modeled, the scientific consensus is that the average annual global temperature would rise another 0.9°C to 1.8°C. As *Display 9* shows, this small temperature change would have adverse consequences. These negative effects, however, are far less catastrophic than the consequences of a 4°C increase that scientists expect to occur if atmospheric concentration of CO_2 rises to 750 ppm.

The potential catastrophic consequences include a rise in sea levels that would submerge areas where tens or even hundreds of millions of people live and work, including much of the Netherlands, Bangladesh, southern Florida and the southern part of Manhattan. It is fear of such catastrophic consequences that is driving the emerging global consensus that strict regulations to reduce greenhouse-gas emissions must be adopted. ■

Display 9

The Consequences of Rising Temperatures Would Be Severe

Atmospheric Concentration of CO_2 (ppm)	Equilibrium Temperature Change* (Degrees C)	Likely Consequences
425–790	+4	Breakdown of Antarctic ice sheet becomes inevitable, adding five meters to accelerating sea-level rise; increasing odds of uncontrollable feedback effects; all consequences exacerbated
350–620	+3	More than 40% of species will inevitably become extinct
		10%–50% of arctic tundra replaced by forest
315–470	+2	Breakdown of Greenland ice sheet becomes inevitable, causing sea level to rise 7 meters over several centuries†
		Thermal expansion of water submerges about 100,000 square kilometers of dry land
		20%–80% loss of Amazon rainforest
290–320	+1	Himalayan glaciers shrink by 80% by 2030
		Loss of 8% of North American freshwater fish habitat

**Scientific estimate for final temperature relative to 1850–1900 average, given stabilization at specified atmospheric concentrations. Today's average global temperature is +0.8°C. At the current atmospheric concentrations of 380 ppm CO_2, reaching +1.6 to +3.5°C is considered inevitable.*
†The Center for International Earth Science Information Network (CIESIN) estimates that roughly 10% of the Earth's current population lives in coastal areas less than 10 meters above sea level, including 127 million people in China, 63 million in India and 23 million in the US.
Source: CIESIN, IPCC fourth assessment report and AllianceBernstein

[13] Total emitted CO_2. Of this total, 758 gigatonnes remained in the atmosphere while the remaining 452 gigatonnes were absorbed by land and ocean.

OUR GLOBAL EMISSIONS-ABATEMENT SCENARIO

To estimate the magnitude of the investment required to reduce greenhouse-gas emissions and the likely success of such investment, we focused on the largest contributors to the problem—CO_2 emissions and the very large, stationary sources that generate a high share of those emissions—and studied the abatement options. Then we developed a feasible scenario for action and assessed the likely impact of this action on global emissions through 2030.

A Concentrated Problem

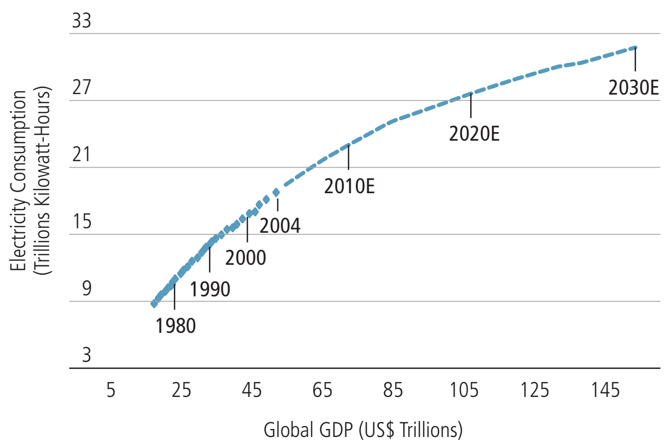
As we explained in "The Science of Climate Change" section, we focus on CO_2 because CO_2 represents the largest volume of greenhouse gases aside from water vapor, which human activity does not directly affect, and has a long atmospheric life cycle of between 50 and 200 years, which multiplies its impact.

Similarly, we focus on electric-power and heat plants because collectively they are the largest source of global CO_2 emissions, at about 36% of total emissions (*Display 10*). Another 30% come from industrial processes that are similar in nature, so that similar abatement measures would apply.

Electric-power and heat plants are also the fastest-growing source of emissions. In 1980, just over 26% of global CO_2 emissions came from electric-power and heat plants. By 1990, that share had risen past 28%. In 2000, it hit 33%. Today, electric-power and heat plants account for 10.8 of the 30 gigatonnes of CO_2 emitted annually. Their increased share reflects the ever-growing use of electricity in computers and consumer electronics, as well as the increased industrialization and higher living standards in much of the developing world. Simply put, economic growth spurs electricity demand, so as the global economy grows, electricity consumption will, too, albeit at a slightly more moderate pace (*Display 11*).

Display 11

Global Consumption of Electricity Grows with the Economy



GDP in year 2000 dollars, measured on a purchasing-power-parity basis
Source: Energy Information Agency (EIA), IMF and AllianceBernstein

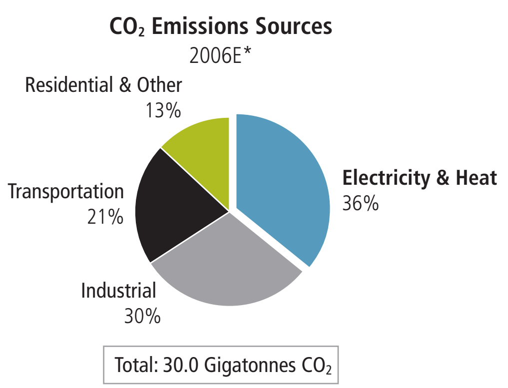
The concentration of CO_2 emissions in the electric-power sector actually makes the problem easier to tackle. It is not necessary to unplug refrigerators or air conditioners, turn off the lights, or do without computers. In 2005, the 150 power plants with the greatest emissions contributed almost 10% of the world's total emissions (*Display 12, next page*). To put this in perspective, shutting down the 150 power plants with the most emissions would have the same impact on atmospheric CO_2 as impounding every passenger car on the planet[14] (not that we advocate either!).

Furthermore, the 1,000 stationary sources with the largest emissions, which include some large industrial factories as well as power plants, contributed 30% of global man-made emissions. The largest 8,000 stationary sources of CO_2, contribute slightly less than half of global CO_2 emissions.

Thus, we expect that the most effective way to reduce CO_2 emissions is to tackle the problem at these 8,000 fixed locations. (We return to the possibilities for reducing emissions from transportation, which contributes another 21% of total CO_2 emissions, on page 77.)

Display 10

Power Generation Is the Largest Source of CO_2 Emissions



**Estimated from 2003 anchor data*
Source: IEA, WRI and AllianceBernstein

[14] Light-duty vehicles account for roughly 40% of overall transportation emissions.

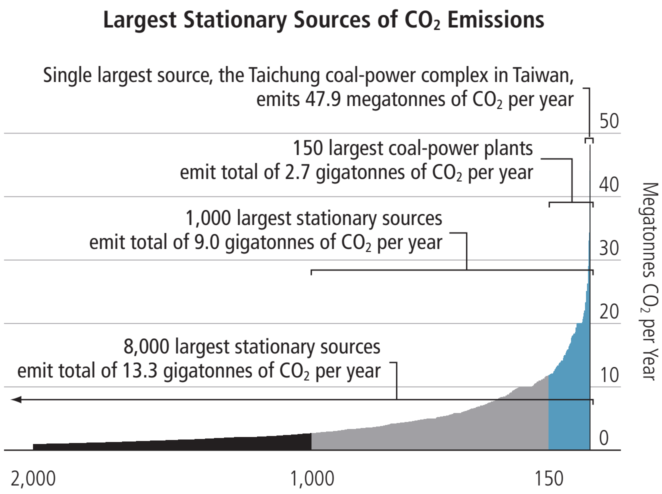
Concentrated Locations

Man-made emissions are also concentrated geographically in the world's industrial centers: the mid-Atlantic and eastern United States, Western Europe, eastern China and Japan. These are all areas with tremendous power requirements, high population density, large coal resources and robust industry. Other notable hot spots lie in India, South Korea and South Africa.

Large-scale CO_2 emissions have spread with industrialization. Historically, Western Europe and the US have been the greatest emitters, and their cumulative emissions remain largest (*Display 13*). But as other areas industrialized, they have caught up. If China, with its massive population, rapidly growing economy, rising living standards and abundant coal resources, has not already overtaken the US as the nation with the greatest annual emissions, it soon will (*Display 14*).

Display 12

Most Emissions Come from Relatively Few Sources



Source: IEA and AllianceBernstein

While nations wrangle over who bears the most responsibility for the world's current situation, it is clear that without concerted efforts to reduce emissions by all the world's largest economies, which are also the largest emitters, emissions will not be reduced as much as most scientists deem necessary. We think that actions already taken by Western Europe and Japan, coupled with shifts in popular opinion elsewhere, make the likelihood of globally coordinated action very high.

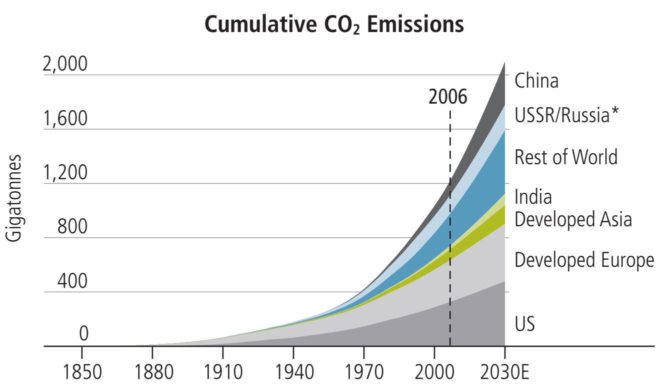
Abatement Options

We identified three key considerations for evaluating abatement options: cost, implementation obstacles (both technical and political) and impact on current lifestyles. We applied these three considerations to evaluate the five possible approaches (*Display 15*).

Do less. The simplest, lowest-cost option for reducing CO_2 emissions is to cut back on activities that require burning fossil fuels for energy: Air-condition, heat and light fewer and smaller buildings; drive less, and pull the plug on televisions and refrigerators. This would significantly reduce the standard of living in the developed world. It would also require putting an end to the rapid industrialization and improvement in living standards in the developing world: telling China and India, for example, to stop building factories and new housing, and to give up on providing electric service to the hundreds of millions of their people now without. Clearly, no country would agree to such a plan, so we crossed it off our list.

Display 13

US and Europe Drove Buildup in Atmospheric CO_2

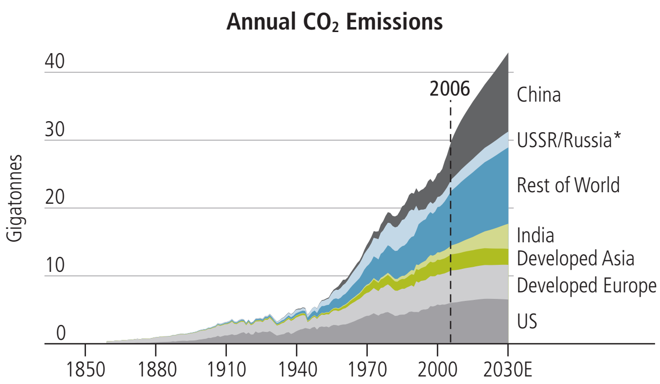


*Prior to 1990, includes emissions of nations once part of USSR; after 1990, those nations emissions included in Rest of World

Source: CDIAC, EIA and AllianceBernstein

Display 14

China Is Taking the Lead in Annual Emissions



*Prior to 1990, includes emissions of nations once part of USSR; after 1990, those nations emissions included in Rest of World

Source: CDIAC, EIA and AllianceBernstein

Display 15

Evaluating the Options for Emissions Abatement

	Cost	Implementation Obstacles*	Impact on Users
Reduce global energy consumption	Low	High	High
Increase natural CO_2 absorption	High	High	Low
Improve energy efficiency	Low	Low	Low
Switch to nuclear and renewables	Moderate	Moderate	Low
Capture fossil-fuel emissions	High	Moderate	Low

Low · Moderate · High

**Technical and political*
Source: AllianceBernstein

Increase natural CO_2 absorption. Strategies for increasing natural CO_2 absorption range from planting more trees and protecting those already planted to bioengineering plants to absorb more CO_2 and dumping 100 tons of iron filings off the Galápagos Islands to incite an algae bloom that would increase ocean absorption of CO_2. Such proposals would have relatively little impact on the lifestyles of most energy users but are likely to prove expensive and to face serious obstacles to implementation. Planting enough trees to make a big difference may not be possible and would cost a great deal while requiring significant redistribution of land. After all, protecting the Amazon rainforest is proving to be an uphill battle! Many proposed bioengineering solutions remain experimental, with high technical obstacles and high likely price tags. And dumping ironing filings in one of the world's most closely protected environments is simply a nonstarter. We don't expect increasing natural CO_2 absorption to be a significant element in reducing atmospheric concentrations.

Do as much with less energy. Improving energy efficiency—by requiring more energy-efficient technologies and building practices and encouraging the use of them by raising electricity prices—would have relatively little impact on users and would not cost much. There are also relatively few implementation obstacles. Although the potential reduction in total carbon emissions is limited, we expect this to become a significant part of global emissions-reduction policy in the near term.

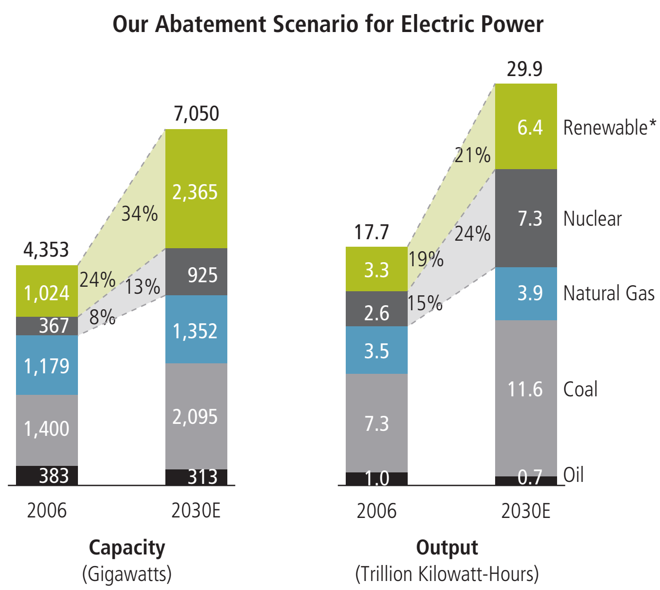
Generate electricity from sources that do not create CO_2. Expanding the nuclear-power fleet and continuing to develop renewable-energy electric generation can significantly reduce global emissions without affecting the lifestyles of end users. While most renewable-energy sources (particularly solar power) are relatively high-cost and face geographic limitations, they have strong political support. Nuclear power, by contrast, is relatively low-cost, but faces political opposition in some regions, although that is waning. Thus, we view nuclear and renewable energy as key elements of a plan to reduce CO_2 emissions from electric-power generation.

Capture and sequester CO_2 emissions from stationary sources. Even with aggressive adoption of energy-efficient measures, an aggressive build-out of renewable energy and nuclear power will not be capable of generating enough CO_2-free electricity to meet growing global demand (*Display 16*). Thus, mankind will continue to require coal-burning power plants. To stop the accumulation of CO_2 in the atmosphere, CO_2 emissions from coal-power plants and other stationary sources must be captured.

This approach does not significantly affect end users, except by raising the price of electricity. Although capturing and storing CO_2 emissions is costly, the cost is likely to decline as the technologies are improved and commercialized. Political support for this abatement option is significant, and the remaining technical issues regarding implementation are surmountable. Hence, we expect carbon capture and storage to become an important strategy for abating CO_2 emissions.

Display 16

Nuclear and Renewable Energy Will Not Be Enough



**Renewable energy includes hydroelectric, solar, wind, geothermal and biomass power.*
Source: EIA, IEA and AllianceBernstein

OTHER WAYS TO LAY BLAME

Judgments about which nations are most to blame for greenhouse-gas emissions will differ based on whether you look at total national emissions or adjust for the size of the population or economy.

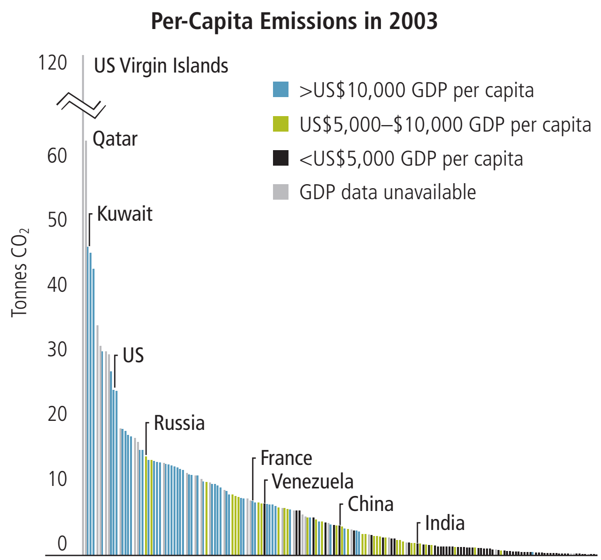
Globally, mankind emits four tonnes of CO_2 per person per year. On a per-person basis, the leading emitter is the US Virgin Islands, a sparsely inhabited tourist destination, which emits 125 tonnes per resident. (The exclusion of tourists, who contribute a great deal to the territory's emissions, from the population data leads to the high level of per-capita emissions.) Next come oil-producing nations such as Qatar and Kuwait, which emit 62 and 33 tonnes per resident, respectively (*Display 17*).

The major developed nations are below this level, but still well above the global average: The 20 developed nations in the Organisation for Economic Co-Operation and Development (OECD) emit 13 tonnes per person, with the US at 20, commodity-producing Australia and Canada at 18, Japan at 10 and Western European nations, on average, at 8. France stands out among developed nations, with CO_2 emissions of just 6 tonnes per person, largely because of its heavy reliance on nuclear power. China and India emit only 3 tonnes and 1.2 tonnes per person, respectively. Their still-low levels of energy consumption per person offset their heavy reliance on coal.

Looked at another way, the world emits 0.5 kilograms of CO_2 per US dollar of GDP (measured on a purchasing-power-parity basis, using the value of the dollar in 2000). On this measure, the largest emitter is Uzbekistan, which emits 3.0 kilograms of CO_2 per dollar of GDP. The OECD nations on average emit 0.4 kilograms of CO_2 per dollar of GDP, with the US at 0.6, Japan at 0.4 and Western Europe on average at 0.3. France is once again on the low end of the range, with emissions of only 0.2 kilogram per dollar of GDP, and oil-producing nations and commodity-rich countries are once again much higher than the world average. ■

Display 17

Emissions per Person Rise with Income and Cheap Fuel



GDP in year 2000 dollars, measured on a purchasing-power-parity basis
Source: World Bank and AllianceBernstein

In sum, we expect regulations aimed at reducing CO_2 emissions to encourage increased reliance on nuclear and renewable power sources and to prompt some efficiency improvements, but we expect that those policies alone cannot grow rapidly enough to provide the vast amounts of electricity that the world will require. As a result, mankind will have to continue to burn fossil fuels, particularly coal, to create electricity and heat. Therefore, to meaningfully reduce greenhouse-gas emissions, the world will have to adopt policies that encourage or require capture and safe storage of the CO_2 emitted as a by-product.

Two Scenarios

How much of a difference could such regulations make?

To understand how CO_2 regulations would affect investment opportunities in the power sector, we developed two detailed models of the build-out of the global power-generation infrastructure from now to 2030. The first model is our business-as-usual case. In this scenario, we tried to predict the actions of power producers if current CO_2 regulations lapsed and no new actions to mitigate atmospheric concentrations of CO_2 were taken. In the second model, our emissions-abatement scenario, we assumed that investments in power would have to comply with either a multinational post-Kyoto pact or a series of regional agreements that result in widespread emissions regulations of increasing severity and breadth. We believe that the abatement scenario will much more closely resemble the future of global power investments.

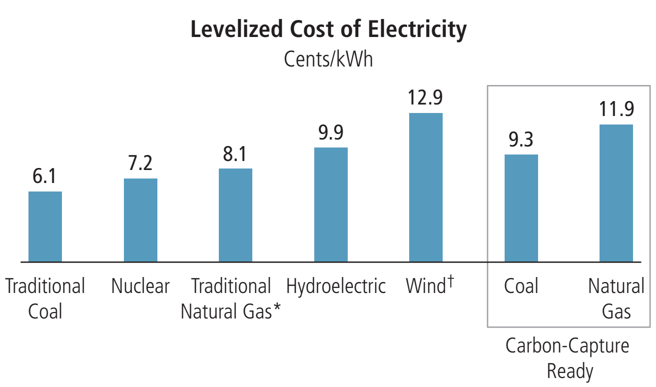
Not surprisingly, the two cases lead to very different outcomes. In our business-as-usual scenario, concerns about energy security and cost considerations lead to greater reliance on coal-based power generation without carbon capture. In the abatement scenario, the global power fleet is transformed by a shift to CO_2-emissions-free power: Nuclear power enjoys a renaissance, coal becomes clean and renewable energy gains a greater foothold.

In developing these scenarios, we adopted the perspective of the world's power-generation developers, making strategic decisions about whether to rebuild, retrofit or raze each plant in the most economically rational manner possible. We took into account such practical considerations as construction times, regulatory risks, fixed and variable costs and political uncertainty, to name just a few. Like any power producer, we sought to meet continued growth in demand for electricity with the lowest-cost technology, given the particulars of the local and global environments.

Carbon constraints dramatically change the calculation. We calculated for different types of power plants the levelized cost of electricity, defined as the average price that a power producer would have to charge over the course of the plant's lifetime to generate an acceptable rate of return on invested capital. When there are no regulations that directly or indirectly impose a cost on CO_2 emissions, coal plants produce electricity most cheaply (*Display 18*).

Display 18

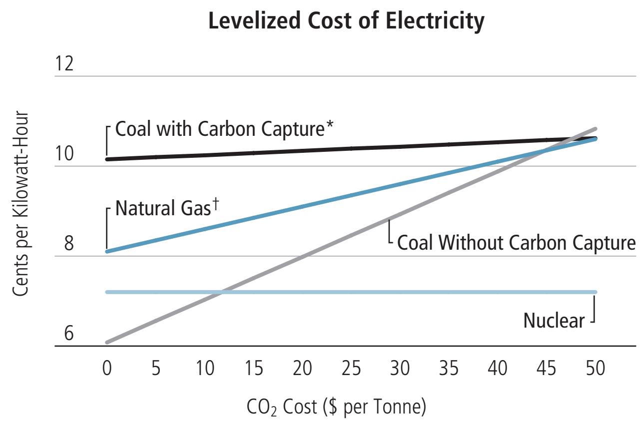
At No Cost for CO_2, Coal Is Most Economical Option



For solar power, levelized cost is 58.2 cents per kilowatt-hour.
**Assumes natural gas costs $8 per million BTUs*
†*Excludes cost to integrate intermittent power into electric grid and cost of backup power*
Source: IEA and AllianceBernstein

Display 19

If There's a Cost for CO_2 Emissions, Nuclear Is Cheapest



**Includes cost to transport and store CO_2*
†*Assumes natural gas costs $8 per million BTUs; without carbon capture*
Source: IEA and AllianceBernstein

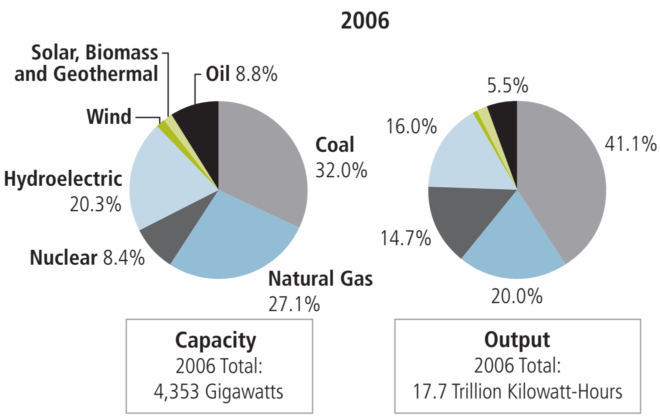
As shown in *Display 19*, however, once regulations impose a cost for CO_2 emissions of at least $12 per tonne, traditional coal power is no longer the source of electricity with the lowest levelized cost: Nuclear power becomes cheapest. Furthermore, once the cost for CO_2 emissions reaches $50 per tonne, it becomes more economical for power producers to build a coal plant that can capture CO_2, and to pay for transport and storage, than to build a new coal or natural-gas plant that spews CO_2 into the atmosphere.

Because companies that build power plants are making capital investments that will stay on their balance sheets for many decades, their decisions reflect their expectations for costs and potential regulatory requirements in the future. Hence, the current heightened interest in nuclear power and burgeoning interest in carbon-capturing coal plants.

In this section, we summarize the results of our simulations and research. Since we believe that global CO_2 regulation is inevitable, we are in effect presenting our investment case (the emissions-abatement scenario) versus a baseline (the business-as-usual scenario). The difference between these two scenarios represents the investment opportunity that the market at large may not recognize. For more detail on the assumptions, regional differences, practical considerations and technological advances that underlie this investment case, as well as a more granular presentation of the results, please refer to Appendix A, Our Power-Generation Model in Detail, on page 97.

Display 20

Coal Plants Dominate Power Generation Globally



Source: EIA, IEA and AllianceBernstein

The Current State of the Global Power Fleet

Currently, the world relies most on coal for electric-power generation (*Display 20*). Coal-power plants account for 32% of global capacity and, because of their relatively high utilization rates, represent over 41% of electricity generation. Coal provides consistently cheap base-load electricity from plants that operate almost around the clock. In some regions, plants operate on average more than 6,000 of the 8,760 hours in a year.

In most developed countries, however, the coal fleet is aging. In the US and developed Europe, most of the coal-power infrastructure is over 35 years old. While these plants could potentially run for another 15 years (or even longer), regulations governing emissions of CO_2 and other pollutants such as sulfur dioxide, mercury and nitrogen oxides (NOx),[15] will likely force operators to either retrofit these plants or retire them. In the developing world, most notably in China and India, much of the large-scale coal-power infrastructure is relatively young. It was built to cope with burgeoning electricity demand in recent years related to rapid economic growth and development. In short, the developed world's coal-power fleet faces a potential replacement cycle, but the developing world's coal fleet is still being built—at an astoundingly rapid pace.

Natural-gas plants account for 27% of the world's total capacity and 20% of global supply. The discrepancy reflects the fuel's benefits and drawbacks. Natural-gas plants can be built quickly and at low cost relative to coal or nuclear plants and can be turned on or off relatively quickly and easily. Thus, they are suitable for providing capacity to meet peak demand. Natural-gas plants emit roughly half as much CO_2 and less mercury and other pollutants than coal plants, which has also made them attractive.

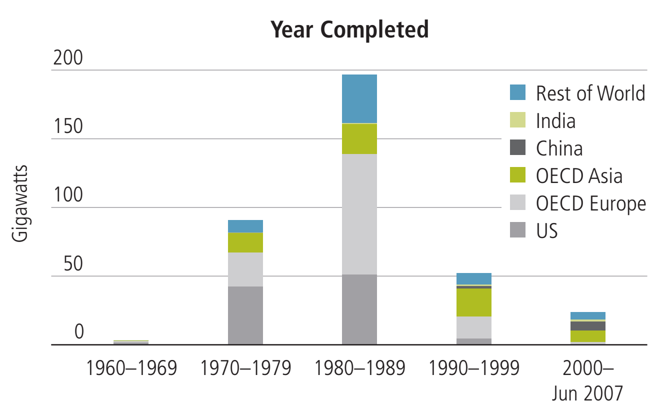
Their downside is that the marginal cost of electricity generated from such facilities is largely driven by the price of natural gas, which is remarkably volatile. In addition, the scarcity of reserves in the US and developed Europe has contributed to increased concerns about energy security. The shortage of reliable, low-cost natural gas supplies prevents natural-gas plants from being consistently economical providers of electricity for base-load purposes.

Nuclear power makes up roughly 8% of global capacity and nearly 15% of global electricity output. New plants require a very large initial capital outlay and may take up to seven years to construct. In many countries, it takes even longer to get approvals. Once started, however, the plants are expensive to shut down. The polar opposite of natural-gas plants, nuclear-power plants require huge up-front costs but their operating costs are relatively low and less sensitive to fuel prices. Thus, nuclear power tends to be suitable for base-load power generation. Globally, nuclear-power plants run for more than eight out of every 10 hours; in the US, they run more than nine out of 10.

But the world's nuclear infrastructure is aging (*Display 21*). More than 80% of global capacity was built prior to 1990 and more than 25% came online in the 1960s and 1970s. Most nuclear-power plants have a stated operational life span of 40 years; in some cases, their operating lives can be extended to 50 or 60 years. Even without new CO_2 regulation, a large part of the global fleet will have to be replaced or abandoned. CO_2 emissions regulations would make the future build-out a great deal larger.

Display 21

The Nuclear Fleet Is Aging, Especially in the US and Europe



Source: International Atomic Energy Agency (IAEA) and AllianceBernstein

[15] Includes nitrogen oxide (NO) and nitrogen dioxide (NO_2), a toxin that reacts with the atmosphere to form smog. N_2O, the greenhouse gas, is also a nitrogen oxide, but it is not emitted by power plants or automobiles.

Hydroelectric and oil-based power plants are the last major pieces of the current fleets, at about 20% and 9% of total capacity, and 16% and 6% of global supply, respectively. In the developed world, both are unlikely to expand much, if at all, but hydroelectric power may grow in developing countries—particularly China, India and Brazil—in the near to intermediate term. Hydroelectric-power plants require significant initial investments, but can last for 100 years or longer. Some hydroelectric plants operating in Europe date back to the nineteenth century! They are also relatively cheap to operate. Oil-fired power plants, while relatively cheap to build, are subject to even greater fuel-price volatility and supply constraints than natural-gas plants. In countries where oil is inexpensive, oil-power plants remain a viable source of electricity, but almost no new oil-power plants are being built today in the developed world.

Aside from hydroelectric power, renewable energy still provides a small share of the world's power, despite increasing political and public support. In aggregate, wind, solar, biomass and geothermal power provide less than 3% of all electricity generated.

For wind and solar power, in particular, utilization rates are low because power can only be generated when the wind is blowing or the sun is shining. The unpredictability of output also makes it difficult to dispatch the electricity generated. Finally, the best resources are frequently not located where they would be most useful.

Biomass power (which generates electricity from sugar, corn, wood chips, grasses and other plant matter) is more predictable but requires a great deal of land. The World Energy Council estimates that biomass power could meet global electricity demand—if cropland exceeding the size of the continental US were dedicated to that purpose.

Geothermal power is also a predictable source of energy. However, it is available only in limited locations and requires significant capital investment without certainty of reasonable output.

These factors contribute to the relatively high costs that make most investment in many kinds of renewable energies economically irrational without subsidies. As such, these technologies have generally penetrated markets only with government financial support.

Estimating Future Demand

Next, we sought to develop long-term projections of global electricity demand. We examined electricity demand today on a regional basis and compared it with both GDP and population growth estimates, and consulted with a number of experts on the demographics and economics of various regions.

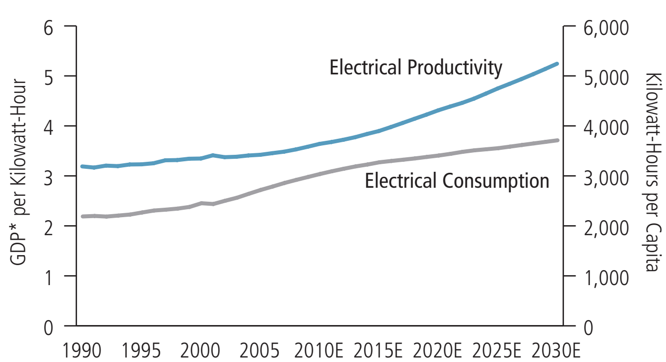
Our projections explicitly take into account the likely influence of improved electrical efficiency across industries and geographic regions and the elevated power demands that will likely come with the rise of plug-in hybrid electric vehicles, as well as the electrification of India and other developing countries. We expect that electricity will be made available to far more homes but that most industries will be able to increase production while using less power.

In 1990, the world consumed roughly 2,100 kilowatt-hours of electricity per capita, while producing a little over US$3.10 worth of GDP output for every kilowatt-hour consumed[16] (*Display 22*). In 2006, the world consumed over 2,700 kilowatt-hours per capita while producing nearly $3.40 of GDP output per kilowatt-hour.

We expect these trends to continue and even accelerate. We project that the world will consume more than 3,600 kilowatt-hours per capita by 2030, leading to a near-doubling of electricity demand to roughly 30 trillion kilowatt-hours from 17.7 trillion kilowatt-hours in 2006.[17] But GDP per kilowatt-hour consumed will also rise, to more than $5 in inflation-adjusted terms.

Display 22

Electrical-Productivity Gains Will Outpace Electric Consumption

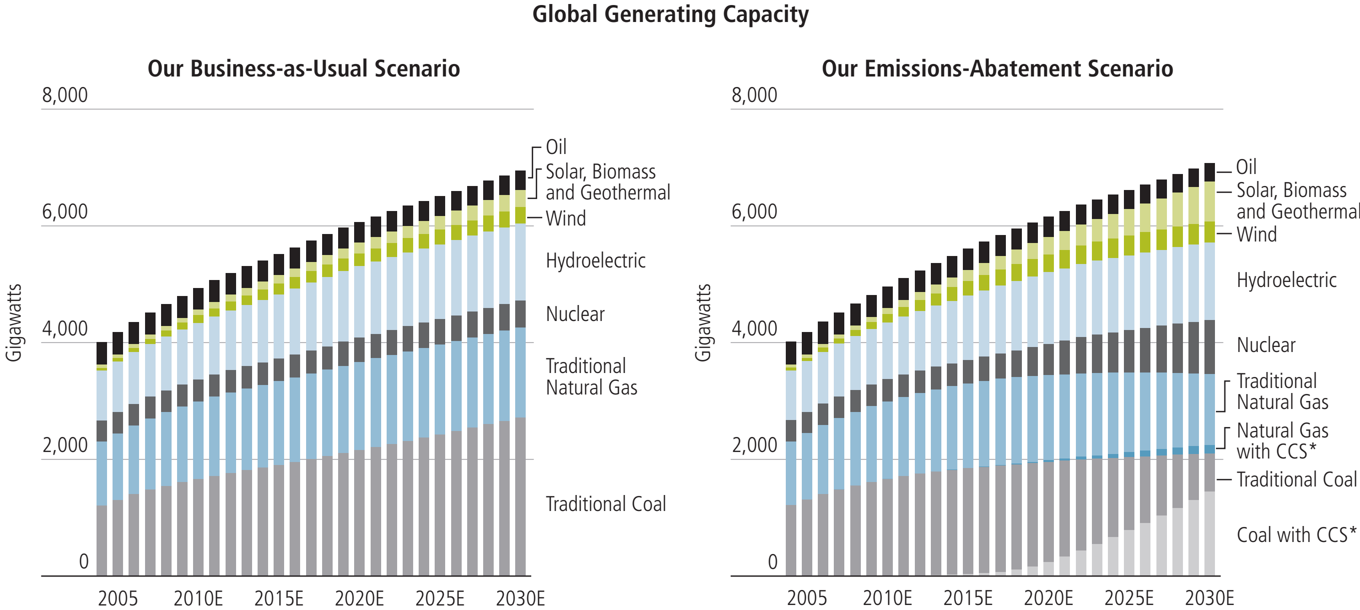


**Constant year 2000 dollars measured on a purchasing-power-parity basis*
Source: EIA, World Bank and AllianceBernstein

[16] Dollar values in constant 2000 dollars, measured on a purchasing-power-parity basis, from the EIA.

[17] This estimate accounts for both incremental electricity demand because of the adoption of plug-in hybrid vehicles and the reduction in demand spurred by the spread of electrically efficient technologies. These two factors roughly offset each other, accounting for a little under 3 trillion kilowatt-hours of demand and demand-destruction, respectively. The EIA forecasts electricity generation in 2030 of 30.4 trillion kilowatt-hours.

Display 23
Climate-Change Concerns Will Dramatically Change the Mix of Power Plants



**Carbon capture and storage*
Source: EIA, IEA and AllianceBernstein

Thus, we do not expect new regulations to lead to the reduction in living standards that would occur if people were forced to use less electricity or fewer people were given access to electricity. Instead, we expect new regulations to lead to a transformation of the electric-power infrastructure that will lower carbon emissions, raise electricity prices and prompt more efficient use of electricity.

Implications for the Power Mix

In a world without carbon constraints—our business-as-usual scenario—rising demand for electricity would lead to building many more traditional coal-power plants. Coal's abundance and price stability, not to mention coal-power plants' proven reliability, would lead to continued investment in worldwide coal capacity. If CO_2-emissions regulations are not adopted, we would expect to see coal-fleet capacity quadruple in India, double in China and almost double worldwide by 2030 (*Display 23, left*).

Even with emissions regulations, we expect coal to continue to contribute meaningfully to global electricity supplies and retain the largest share of global electric-power generation: We project that coal-power capacity will rise from 1,400 gigawatts to almost 2,100 in 2030, with its share of total electricity generated falling from 41% in 2006 to 39% in 2030. But coal power would be transformed by the implementation of carbon-capture and storage technologies. We expect that by 2030, only slightly more than 30% of the coal fleet will be traditional plants that release most of their CO_2 into the atmosphere (*Display 23, right*).

In fact, we expect that by 2030 there will be more carbon-capturing coal capacity online than there is traditional coal capacity today. This clean coal capacity[18] will likely be buttressed by a large increase in nuclear-power capacity (from 367 gigawatts in 2006 to over 900 in 2030) and by additional hydroelectric development in China, India and the rest of the developing world.

The Investment Flows Ahead

There is good visibility about near-term power-generation capacity growth. Electric-power plants are planned far before construction starts because of their size, complexity and enormous impact on the electric grid and environment. While details vary by country, operators generally have to apply for a license, negotiate fuel- and power-purchase agreements, and often have to placate environmentalists, consumer advocates, labor unions and other community groups. Even after construction begins, it may take years before power generation starts. Most of the facilities that will begin

[18] Carbon-sequestration technologies can capture roughly 90% or more of the CO_2 emissions from coal plants.

to operate over the next five years have already been announced, financed and celebrated (or decried). In many cases, the foundations have already been poured, and the walls have begun to rise.

In the near term, the ample information about plans under way shows capital spending on power infrastructure will be much like that in the recent past. In each of the last two years, global capital spending on power-generation infrastructure has exceeded $200 billion, with about $90 billion a year spent on coal-fired plants and roughly $40 billion, $30 billion, $20 billion and $10 billion on natural-gas, hydroelectric, wind and solar power, respectively. The remaining $10 billion a year was distributed between nuclear, biomass and oil-power plants.

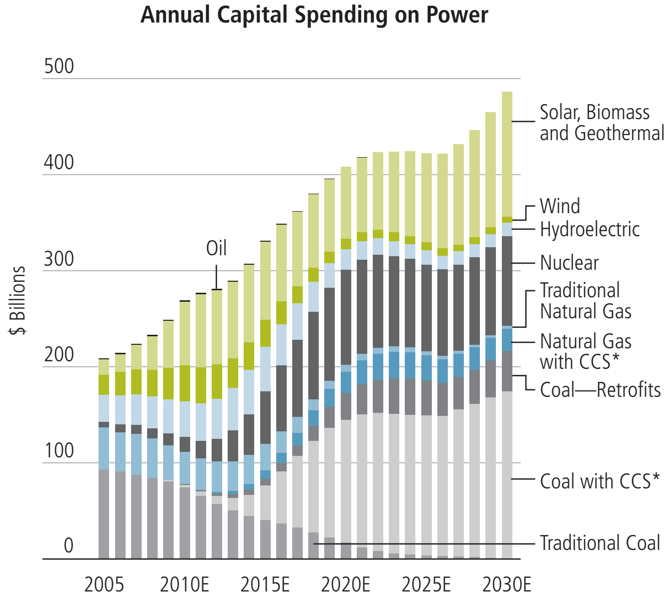
We expect the developed world's spending on natural-gas plants to decline in the next three years as CO_2 regulations solidify, providing power producers with the long-term clarity required to make larger capital investments. We also anticipate a sharp decline in spending on wind power early in the next decade, when we project that most of the best sites will already have been exploited. We expect the developing world to continue to rapidly expand its already massive coal-power fleet and aggressively exploit its remaining hydroelectric resources.

In the medium and long term, however, our emissions-abatement scenario for spending looks quite different from the present or our business-as-usual scenario. Many power producers (and governments) have already begun to prepare for more stringent CO_2 regulation by planning new nuclear reactors. Depending on the local or regional regulatory framework, it may take as long as a decade to produce the first kilowatt-hour of electricity from new nuclear plants. We do not expect many to come online until 2015 or later.

We think that few companies will commit to investments in carbon capture and storage infrastructure for coal or natural-gas plants prior to gaining certainty about regulatory requirements. The cost of creating a clean coal facility, in particular, is simply too high for utilities to risk making an investment that may prove unnecessary for meeting regulatory requirements. Since we expect the CO_2-emissions rules to be fairly clear by the end of this decade and carbon-capturing coal plants take about five years to build, we don't project widespread adoption of clean coal technology until after 2014.[19]

Display 24

Coal and Nuclear Will Gain Most from Abatement Efforts



In constant 2007 dollars

**Carbon capture and storage*

Source: EIA, IEA and AllianceBernstein

We project that construction of traditional coal plants in developed countries will likely decline prior to 2014 as businesses recognize that investments in traditional coal plants may require significant follow-up investment to satisfy future emissions standards. Some power producers may, however, opt to build coal-power plants that are ready to be retrofitted for carbon capture (as the European Union will likely require). They would then install CO_2-capturing technology when the cost of carbon emissions has risen high enough to justify the expense.

Retrofits of coal-power plants will likely begin in developed countries prior to 2015 and spread throughout the world by the early 2020s. Retrofitting a coal-power plant effectively reduces the electricity output of the facility by 30%–40%, depending upon the technology used. The resulting capacity loss, combined with the capacity loss from retiring many, mostly smaller, plants that are not worth retrofitting, will require a much more robust replacement cycle for the power fleet in general and for the coal and nuclear fleets in particular. Since the bulk of nuclear-power retirements and replacements will likely occur at about the same time as the retrofitting and replacement of existing coal capacity, we expect 2015–2020 to be a period of massive spending growth on power-generation infrastructure (*Display 24*).

[19] Our capital-expenditure calculations take into account the money spent during construction prior to bringing the plant online. Thus, some of the money required to bring a coal-power plant into service in any one year appears as spending in the prior years when the plant is under construction.

In the late 2020s, we predict, the developing world will still be adjusting to tighter emissions limits by retrofitting and replacing old coal-power plants. In addition, we expect countries with ready access to natural gas, such as those in the Middle East, to adapt carbon-capture technologies to natural-gas plants. Around the world, countries will likely supplement their existing base-load electric-power capacity with an expanded nuclear fleet. We expect much of the developing world's politically and economically viable hydroelectric resources to be fully exploited by this point. If solar power becomes truly cost-competitive with other peak-power technologies (after 2020 in our model), we expect sizable investment flows into that segment to begin.

Key Differences Between Scenarios

Our emissions-abatement and business-as-usual scenarios differ markedly in several places.

First, investment in power generation will grow substantially as a result of emissions abatement (*Display 25*). Investments will more than double from current levels of $200 billion a year by 2020 and reach over $450 billion a year in constant dollars by 2030. Our business-as-usual case calls for only $190 billion in 2020 and $210 billion in 2030.

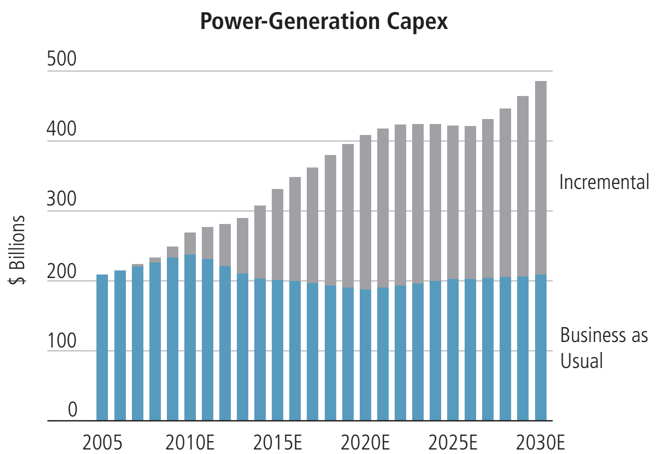
Second, we expect the fervent political interest in renewable energy sources (aside from hydroelectric power) to die down as it becomes increasingly clear that the substantial funds devoted to subsidizing renewable energy actually produce relatively little power. Although CO_2 regulation will likely make some marginally economic wind projects more attractive and increase somewhat the duration and magnitude of wind-generation infrastructure spending, growth will ultimately be limited by the small number of wind resources in close enough proximity to electricity-demand centers. Solar power, on the other hand, will only become truly compelling if it becomes cost-competitive, which we do not expect before 2020, if at all. The need for relatively inexpensive base-load power will drive developing countries to exploit their remaining hydroelectric resources regardless of CO_2 regulations. Thus, spending on hydroelectric power does not appreciably vary in a business-as-usual versus emissions-abatement scenario.

Third, from the end of this decade to the end of the next, our emissions-abatement scenario calls for significantly greater investment in nuclear power than our business-as-usual case (*Display 26*).

Fourth, our emissions-abatement scenario calls for much more spending on coal than our business-as-usual case. This reflects the higher cost of clean coal technology and the capacity that would have to be replaced because of retrofits and retirements. We predict that global capital spending on coal will rise from roughly $90 billion per year today to roughly $190 billion before 2025, with the big surge coming after 2015.

Display 25

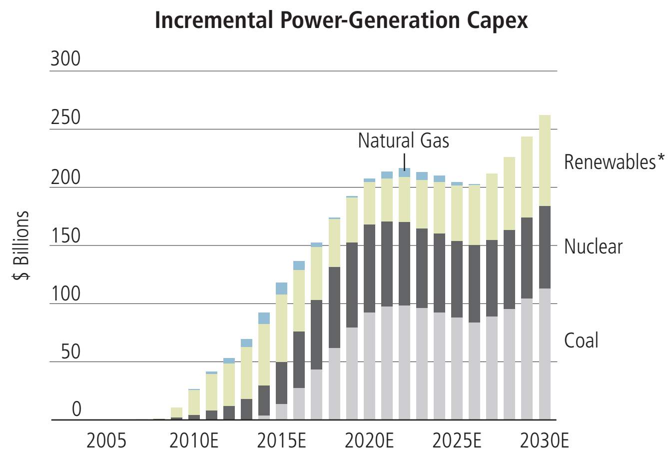
Abatement Efforts Will Add Hugely to Global Power Capex



In constant 2007 dollars
Source: EIA, IEA and AllianceBernstein

Display 26

CO_2 Regulation Will Boost Nuclear and Coal Capex Most



**Renewable energy includes hydroelectric, solar, wind, geothermal and biomass power.*
In constant 2007 dollars
Source: EIA, IEA and AllianceBernstein

How Much Will Emissions Fall?

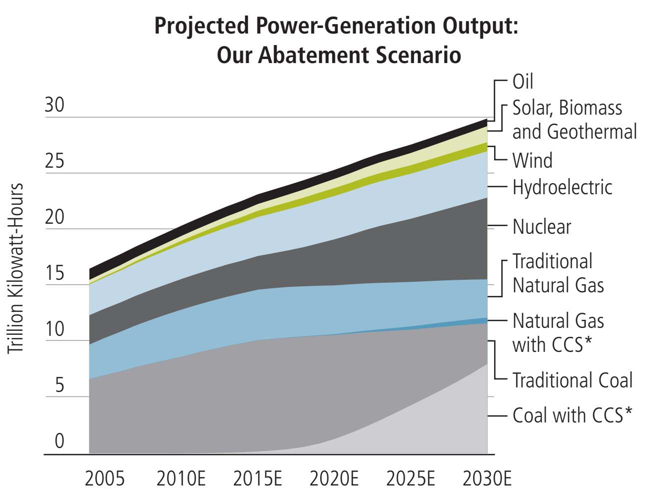
We expect the vast incremental spending on electric generation aimed at carbon-emissions abatement to produce a remarkably clean array of global power options. By 2030, we expect that almost three-quarters of electricity generated will come from clean or near-clean[20] technologies, with carbon-capturing coal and nuclear power each providing roughly 25% of the world's electricity (*Display 27*). Nuclear, solar and wind power will gain share. Natural-gas plants' share of total electricity generated will fall from 20% in 2006 to 13% in 2030. Hydroelectric power will also lose share.

We also predict that conversion to these clean technologies will significantly reduce global CO_2 emissions from the power sector (*Display 28*). This transformation of the power fleet could reduce global CO_2 emissions from the electric-power sector from 10.8 gigatonnes in 2006 to roughly 6.3 gigatonnes a year by 2030—less than the 6.4 gigatonnes emitted in 1990, despite almost three times more electricity generated. Without this transformation, we project that annual electricity-sector emissions would reach 16.4 gigatonnes by 2030.

We also modeled expected emissions from the industrial, residential and transportation sectors. Industrial emissions are typically concentrated in large stationary sites that in many cases can be abated with the same CO_2 capture and storage technologies used in coal and natural-gas plants. We expect the transformation of industrial sources to mirror that of the power sector. However, we expect governments to move more slowly to require CO_2 capture from industrial companies because they are subject to greater foreign competition than power plants. To protect jobs, many national governments may delay applying regulations (as the EU has done).

Display 27

The Fuel Mix for Power Generation Will Change Dramatically

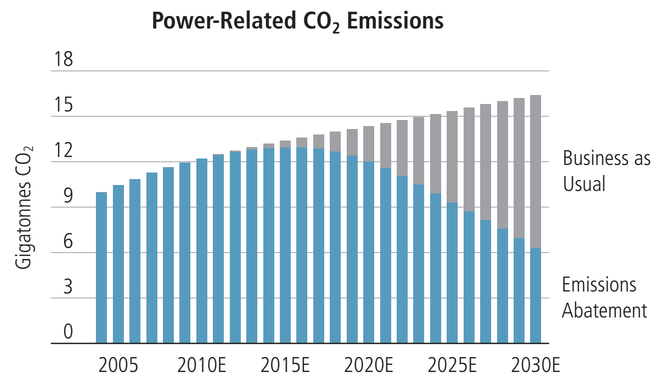


**Carbon capture and storage*

Source: EIA, IEA and AllianceBernstein

Display 28

Abatement Efforts Will Cause Power-Related Emissions to Fall



Source: EIA, IEA and AllianceBernstein

Within transportation, we take into account the widespread adoption of plug-in hybrid vehicles that we expect. As we discussed in a previous report,[21] we expect hybrid vehicles to significantly reduce demand for oil—and thus carbon emissions—from the global transportation sector. Plug-in hybrids, which can run on a battery charged off the electric grid, shift carbon emissions from the car's tailpipe to the power plant's flue, where they can be captured. We do not foresee significant emissions reductions in air transport and shipping. (Railroads are not a significant source of emissions.)

Finally, we expect the residential sector to reduce emissions somewhat, as regulation inspires more efficient use of fossil fuels for heating and cooling, and as building standards become more stringent.

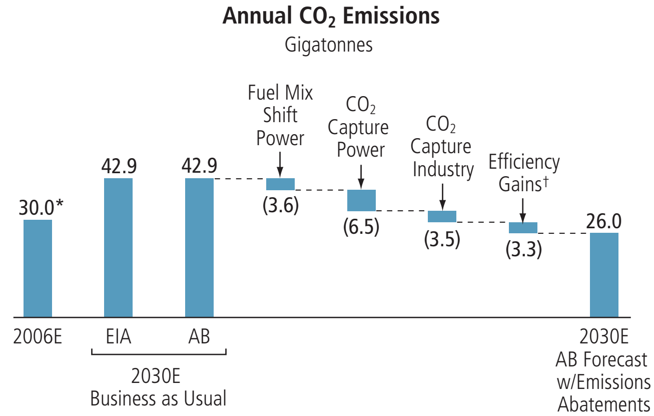
Theoretically, turning to emissions-free or near-free electric-power technologies, applying carbon-capture technologies to other energy-intensive industries, and shifting the road transportation sector to plug-in hybrid vehicles could abate about 90% of total CO_2 emissions. We do *not* predict such a massive conversion in the foreseeable future.

[20] Carbon-capturing technologies for natural-gas and coal power are expected to capture roughly 90% of the carbon dioxide emitted.

[21] Amy Raskin and Saurin Shah, *The Emergence of Hybrid Vehicles: Ending Oil's Stranglehold on Transportation and the Economy* (AllianceBernstein, 2006)

Display 29

Emissions-Control Efforts Could Make a Big Difference



Estimated from 2003 data

†*Includes impact of widespread adoption of hybrid vehicles*

Source: EIA, IEA, Oak Ridge National Laboratory (ORNL), WRI and AllianceBernstein

Our business-as-usual scenario calls for global annual CO_2 emissions to rise from 30 gigatonnes in 2006 to almost 43 gigatonnes by 2030. Under our emissions-abatement scenario, emissions will fall to 26 gigatonnes a year by 2030 (*Display 29*). More than 10 gigatonnes of the 17-gigatonne drop in emissions will come from changing the fuel mix in power generation and capturing CO_2 from fossil-fuel-fired plants. The balance will come from similar efforts in industry, as well as the shift to more energy-efficient technologies of various kinds, including transportation. Cumulatively, we predict that emissions-abatement efforts will result in almost 120 gigatonnes less CO_2 emissions between 2010 and 2030 than would otherwise occur.

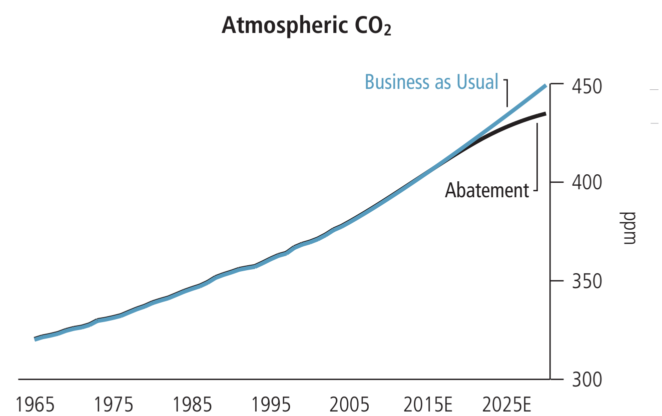
The aggressive carbon regulations that we model would likely have a dramatic, if delayed, impact on the makeup of the atmosphere. While growth in atmospheric concentrations of CO_2 accelerates in our business-as-usual scenario (*Display 30*), in our emissions-abatement scenario, its growth starts to slow after 2015, and by 2030, atmospheric concentrations of CO_2 rise by less than one part per million per year. In our business-as-usual scenario, by contrast, atmospheric concentrations would rise by almost three parts per million in 2030, and this growth rate would continue to climb thereafter.

By making reasonably conservative assumptions about both continued emissions reductions for the emissions-abatement case and continued emissions growth for the business-as-usual case after 2030, we can develop a compelling portrait of how atmospheric concentrations might change over the course of this century. In our emissions-abatement scenario, we expect that concentration levels would peak at less than 450 parts per million by about mid-century. By 2100, concentration levels would likely decline to below 2020 levels. Without emissions controls, however, we would expect atmospheric concentrations to rise to over 500 parts per million before 2050 and to more than 700 by 2100 (*Display 31*).

In the following sections, we will examine the fastest-growing options for generating electricity, according to our emissions-abatement scenario: coal, nuclear and renewable energy. ■

Display 30

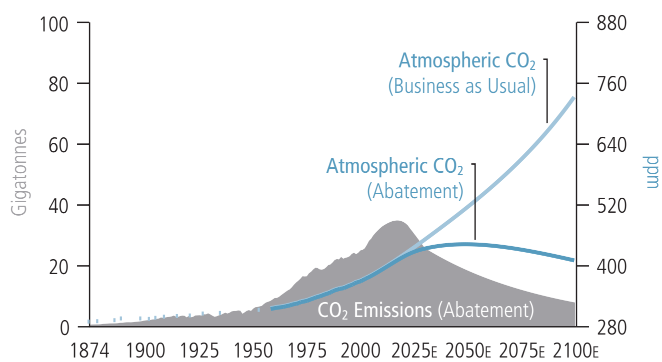
Atmospheric CO_2 Benefit for Abatement Begins After 2015



Source: CDIAC, EIA, IEA and AllianceBernstein

Display 31

Emissions and Atmospheric CO_2 Level Could Fall in This Century



Source: CDIAC, EIA, IEA and AllianceBernstein

COAL: THE WORLD'S DOMINANT FUEL FOR ELECTRIC GENERATION

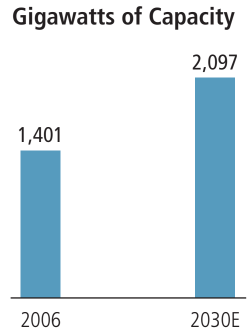
Coal made the industrial revolution possible. Without the discovery that coal could be used to replace the UK's dwindling forests as a fuel to power the steam engine, the UK could not have developed its textile industries or its extensive networks of canal barges and railroads. Later, coal was critical to the development of the steel industry around the world. In the twentieth century, industry and transportation shifted away from coal, but coal became critical for generating electricity. It still fuels about 40% of the electricity generated worldwide, including over 50% of electricity in the US and over 70% in both China and India.[22] Coal is as important to China's rapid industrialization and development today as it once was to the industrialization of the UK and the US.

But except for new plants recently built in China and other developing markets, most existing coal-power capacity was developed decades ago. Stringent environmental regulations aimed at curtailing emissions of sulfur dioxide, nitrogen oxides, mercury and particulates have limited construction of coal-power plants in developed countries over the past 20 years. The electric-power buildup in North America and Europe in the late 1990s was mostly a "dash to gas," as a result of natural-gas plants' lower emissions of pollutants, lower capital costs and shorter time frame for construction and approvals.

Coal technology must soon surmount another obstacle: Burning coal produces more CO_2 per megawatt-hour of electricity generated than any other source (*Display 32*) and almost twice as much as natural gas.

Display 33

We Expect Global Coal-Power Capacity to Grow Nearly 50%



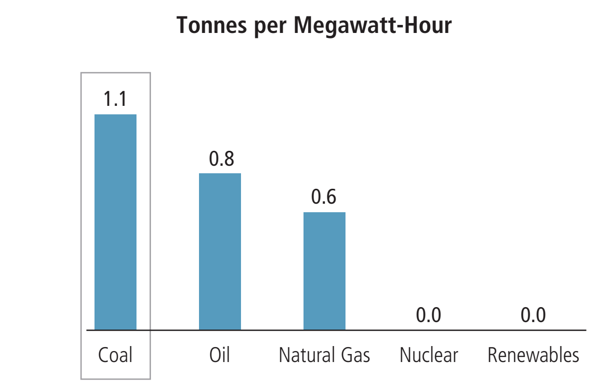
Source: EIA, IEA and AllianceBernstein

Despite these environmental challenges, we project in our abatement model that by 2030, coal-burning electric-generating capacity will increase by 50%, to roughly 2,100 gigawatts (*Display 33*). Simply put, the world needs electricity from coal to support even a moderate rate of global economic growth. The issue is not *whether* coal plants will be built in the future—they will—but *how* they will be built and *how* the carbon they generate will be captured.

Coal has powerful advantages: Most notably, the commodity itself is abundant and widely available and hence persistently cheaper than other fuels (*Display 34*). At current consumption rates, the world has an estimated 142 years of proven coal reserves, compared with 40 years for oil and 64 years for natural gas.[23] Coal reserves are

Display 32

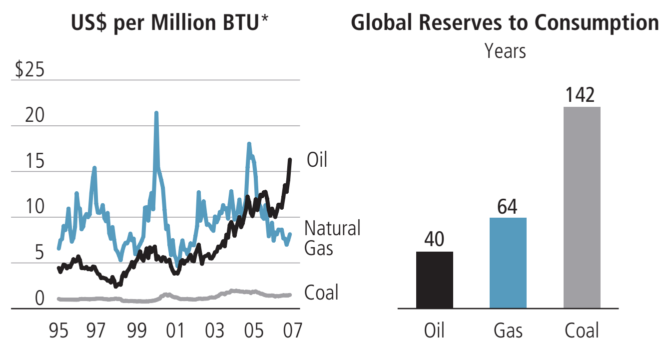
The Problem with Coal: High CO_2 Emissions



Source: IEA and AllianceBernstein

Display 34

Coal Is Consistently Cheaper and More Abundant



* *In 2007 dollars*

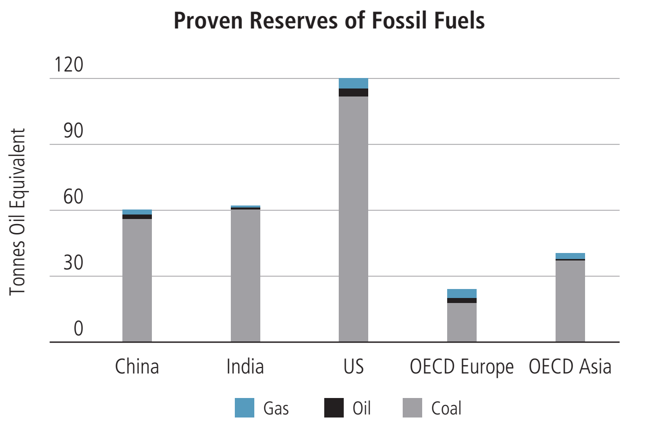
Source: Bloomberg, BP Statistical Review of World Energy, *2006 and AllianceBernstein*

[22] US Department of Energy (US DOE) and EIA *Annual Energy Outlook 2006*

[23] *BP Statistical Review of World Energy*, 2007

Display 35

Local Abundance Makes Coal a Safer Energy Supply



Source: BP Statistical Review of World Energy, *2006*

widely dispersed across the globe, particularly in areas with large and growing energy demand, such as the US, Europe, China and India (*Display 35*). Most oil and gas reserves, by contrast, are far from demand centers and concentrated in less politically stable regions—such as the Middle East, Africa, Russia and Venezuela. Thus, coal presents far less economic security risk than oil or natural gas.

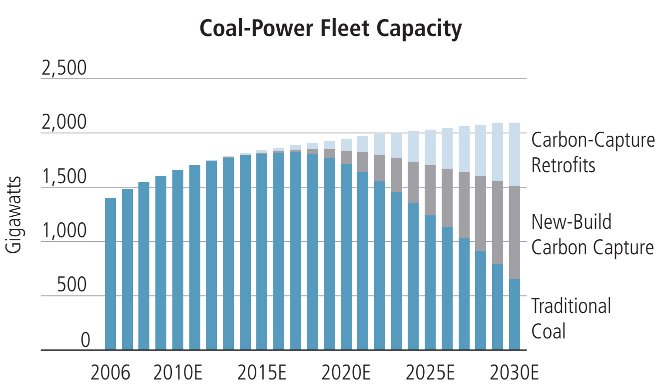
In the last three years, strong growth in electricity demand has triggered a new wave of coal-plant construction. In 2006 alone, over 180 coal plants with a combined capacity of over 100 gigawatts were brought online worldwide. China represented the lion's share of this new capacity, roughly 86 gigawatts. China built as much coal capacity in a single year as the United Kingdom's total fleet for powering its entire economy. We expect China to complete an additional 240 gigawatts before the end of the decade. There are also many projects under way elsewhere: After accounting for the inevitability of some cancellations, we estimate that outside of China, over 170 plants representing over 85 gigawatts of capacity will come online before the end of 2010.

We expect about 2,100 new coal-burning power plants to be built over the next 25 years, with total capacity of 1,700 gigawatts. Without carbon capture, these plants would release as much CO_2 over their 60-year useful lives as *all* the coal burned globally since 1750.[24]

We expect, however, that more than half of new coal capacity will deploy carbon-capture technologies of various types—and so will much of the existing capacity that is not shut down (*Display 36*). With an estimated $1 trillion already invested in the world's existing fleet of coal-burning plants, we expect utilities to retrofit as much of the existing coal fleet as is economically sensible in order to salvage their sunk costs. We estimate that incremental capital spending to retrofit existing coal plants for carbon capture and build new, "clean" coal plants will more than double capital investment in coal power by 2020: The spending will reach $173 billion, versus our $81 billion business-as-usual estimate (*Display 37*).

Display 36

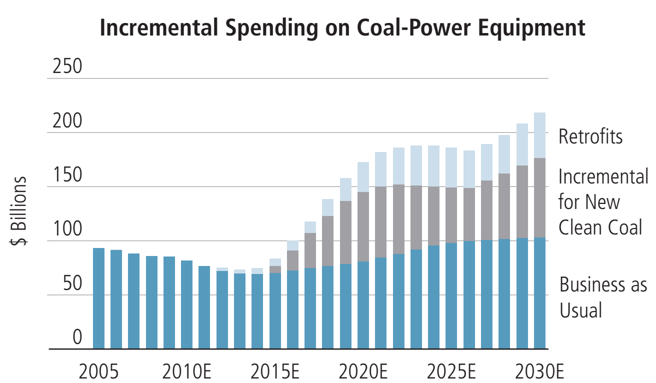
Carbon-Capturing Coal Will Become Increasingly Prevalent



Source: EIA, IEA and AllianceBernstein

Display 37

Capex on Coal Power Will Boom After Regulations Are Clear



In constant 2000 dollars
Source: AllianceBernstein

[24] Over 60 years, 1,700 gigawatts of capacity with a 65% utilization rate and emitting one tonne of CO_2 per megawatt-hour would produce 581 gigatonnes of CO_2. According to the CDIAC, 563 gigatonnes of CO_2 were emitted by burning solid fuels (mostly coal) between 1750 and 2004. Coal emissions in 2005 and 2006 sum to less than 16 gigatonnes.

Display 38

Coal Fleets in the US and Europe Are Aging and Inefficient

	US	OECD Europe
# of Coal-Power Plants	1,580	1,190
Average Size (Megawatts)	225	185
Average Age* (Years)	34	29
Average Efficiency (%)	35	36

**Averaged on a per-megawatt basis*
Source: IEA, Platts and AllianceBernstein

Interim Steps

Many coal-burning plants in the developed world are now old and inefficient: We estimate that the US and European coal fleets are on average 34 and 29 years old, respectively (*Display 38*), and have an average thermal efficiency of 35% and 36%,[25] near the low end of the 34%–43% efficiency range for most modern coal units. Many of these old plants will simply be replaced with cleaner and more efficient plants because it would not be economic to retrofit them. Small units (less than 250 megawatts) that are used only to provide peak-load capacity are particularly likely to be shut down.

The methods now available for retrofitting existing facilities and building new carbon-capture-ready plants would add at least 50% to the cost of coal electricity generation, we estimate. Therefore, utilities are unlikely to employ these methods unless they can recoup the cost via regulatory rate recovery or have other incentives that make the investment worthwhile.

Over the next five years, the coal infrastructure is unlikely to change materially, for several reasons: Some of the carbon-capture technologies are not yet commercially available; the carbon transport and storage infrastructure is not yet in place; and, most important, there are no stringent global emissions limits. In the near term, we expect utilities to get ready for stringent CO_2-emissions regulation by focusing on the lowest-cost options available, such as operational improvements and helping their customers to use electricity more efficiently. They may also shift some production to nuclear, renewable or natural-gas power. Utilities are also likely, in our judgment, to purchase carbon credits to meet their compliance obligations, rather than retrofit facilities, until regulations become more stringent (see Regulation section, page 56).

Such strategies are only short-term solutions. Ultimately, utilities will have to put carbon-emissions control technologies on their coal-fired plants. Our model incorporates a modest number of retrofits between 2010 and 2015, rising gradually through 2020 and increasing significantly thereafter. All in, we expect about 2,100 new plants to be built between 2007 and 2030, of which over 700 will be built with carbon capture and storage from the outset.[26] We expect that over 1,100 plants will be retrofitted. While some of these plants are producing power today, many more are likely to have been designed to accommodate such an upgrade. Over the course of our forecast period, we project that over 50% of the roughly 9,600 coal-power plants in operation will be permanently retired.

Today, the easiest and only immediately viable way to reduce CO_2 emissions from coal-power plants is to improve their thermal efficiency, increasing the electric output per unit of coal burned. Since the CO_2 emissions per unit of coal are constant, increasing thermal efficiency increases electrical output relative to emissions. Plants can increase thermal efficiency by switching to higher-quality coal, increasing steam temperature and pressure, and increasing the utilization rate of the plant.

Improving plant utilization is the most manageable of the three options. Simply put, a coal plant that runs 85% of the hours in a year to meet base-load demand has a higher thermal efficiency than a plant that only runs 30% of the time when electricity demand is near peak levels, because coal plants do not reach their maximum output instantaneously. It takes from several hours to two full days for coal plants to cycle on and off.[27] By contrast, the simple-cycle natural-gas plants used for meeting peak-load demand are designed like a jet engine to reach full efficiency in just a few minutes. Thus, in the developed world, coal plants—unlike natural-gas plants—are seldom built simply to meet peak-capacity needs.

Perhaps as many as one-third of the estimated 9,600 global coal plants in operation in 2006 were old plants that are fully depreciated, but have not yet been shut down. Since these plants are no longer economically

[25] Based on the amount of heat released by a specified quantity of fuel

[26] New plants built with carbon capture are likely to be substantially larger than traditional pulverized-coal plants. Thus, while we expect that two-thirds of the individual *plants* built over the next 23 years will not initially be equipped for carbon capture, we expect that over half of the newly built coal-power *capacity* will.

[27] Some coal plants are cycled on with a cold start, which requires start-up fuel (typically diesel or oil), auxiliary power and additional manpower. Others are cycled on with a warm start, using a boiler or turbine temperature of 250°–700°F, with the plant off-line for 12–48 hours prior to start-up. Still others cycle on with a hot start, with a boiler or turbine temperature of 700°–900°F, with the plant off-line for 8–12 hours prior to start-up.

Display 39

There Are Many Kinds of Coal-Fired Generators

	Fluid-Bed Combustion		Subcritical		Supercritical		Ultra-Supercritical	
Performance	**No Capture**	**Capture***	**No Capture**	**Capture***	**No Capture**	**Capture***	**No Capture**	**Capture***
Generating efficiency	34.8%	25.5%	34.3%	25.1%	38.5%	29.3%	43.3%	34.1%
CO_2 emitted, tonnes/MWh	1.03	0.14	0.93	0.13	0.83	0.11	0.74	0.09
Costs								
Total plant capital cost, $/kWh†	$1,330	$2,270	$1,280	$2,230	$1,330	$2,140	$1,360	$2,090
Fixed cost, US$/kWh	$0.027	$0.046	$0.026	$0.045	$0.027	$0.043	$0.028	$0.042
Variable cost, US$/kWh	$0.020	$0.032	$0.022	$0.036	$0.015	$0.034	$0.019	$0.031
Cost of Electricity, US$/kWh	**$0.047**	**$0.078**	**$0.048**	**$0.082**	**$0.042**	**$0.077**	**$0.047**	**$0.073**

Surveyed design studies incorporated CO_2-capture rates of 86%–88%. Capture rates of up to 90% will likely be implemented.

* *Capture by amine-absorption process*

† *Total plant capital cost normalized to 2000–2004 levels is about 30% lower than capital costs today, because commodity prices and engineering costs have risen substantially over the past three years.*

Source: MIT, The Future of Coal *and AllianceBernstein*

viable for base-load requirements, they are used only sporadically to meet peak or near-peak demand (when prices are higher). Once CO_2 regulations are in effect, these plants will likely become uneconomic to operate even at peak hours. Hence, few operators will be willing to pay to retrofit such plants for carbon capture or to buy carbon offsets for them.

Indeed, as a result of the European Union Large Combustion Plant Directive, which was put into law in 2001, many small coal plants are being retired in Europe. By 2015, we anticipate that as much as a quarter of Europe's coal fleet could be decommissioned. The Chinese government has stated that it intends to shut down 50 gigawatts of small-scale coal capacity prior to the end of 2010; as of August 2007, it claimed to be ahead of schedule in implementing this plan.[28] We expect similar measures to be undertaken in the US, leading to the closing of small, inefficient plants.

Closing coal plants used only for peak capacity is likely to be one way for coal-plant operators to comply with carbon-emissions regulations in the near term. Since peak-hour plants, by definition, only operate for a small number of hours in the year, the impact of closing them on total electric generation and carbon emissions will be fairly small.

Retrofits and replacements of existing plants with carbon-capture technology will likely be the next step for coal-plant operators—and will have far greater impact on electricity output, capital spending and carbon emissions. However, we do not anticipate this happening en masse until after 2015.

Coal-Power Technology Today

Most of the coal plants in operation worldwide and those under construction are air-blown units employing one of several types of pulverized-coal combustion technology. The coal is ground into a powder before it is burned to increase the efficiency of combustion. The heat of combustion is used to generate steam that drives an electric-generation turbine. If there are pollution controls, the flue gas from the boiler passes through scrubbers that remove sulfur dioxide (SO_2) and nitrogen oxides (NOx), the contaminants responsible for acid rain and smog. Then the flue gas, which is 10%–15% CO_2, is vented through the smokestack, contributing to increased concentrations of CO_2 in the atmosphere.

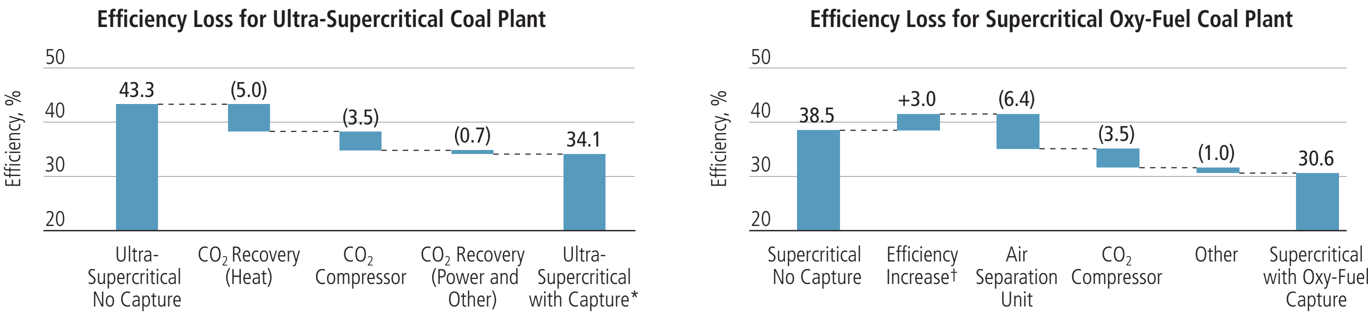
The four main pulverized-coal technologies—circulating fluid-bed, subcritical, supercritical and ultra-supercritical—differ primarily in combustion temperature, steam pressure and the temperature of the cooling water (*Display 39*). The first three are deployed around the world in large-scale plants. Circulating fluid-bed and subcritical power plants are most widespread, but new builds are likely to be supercritical pulverized coal plants because of their favorable economic and environmental trade-off. The thermal efficiency of these four technologies typically ranges between 34% and 43% in a newly built power plant.

Around the world, operators of coal-power plants are implementing SO_2 and NOx emissions controls to alleviate acid rain and smog. To do this, they employ scrubbers that chemically convert these waste gases into solids with industrial uses in gypsum wallboard, cement

[28] The Chinese National Development and Reform Commission

Display 40

Carbon-Capture Retrofits Significantly Reduce Generator Efficiency



* *Capture by amine absorption*

† *As a result of oxy-fuel process, the boiler can operate more efficiently and de-sulfurization of flue gas requires less energy.*

Source: MIT, The Future of Coal

additives, concrete admixture and as fill material for highways. SO_2 and NOx react easily with catalysts, so capturing these pollutants is not unduly burdensome. In all, between the capital outlay to install scrubbers, the additional operation and maintenance requirements, and the scrubbers' parasitic power demand, the units add about 10% to the levelized cost of generating electricity. In regulated markets, utilities have been able to include the added cost in the rate base, so these expenditures have not reduced returns to investors.[29]

The scrubbers are built adjacent to the power plant and do not require material changes in the plant's basic engineering. Furthermore, the scheduled downtime required can be used for a simultaneous upgrade of steam valves and pipes, which may have otherwise happened later. Thus far, our research shows that the improved efficiency from new valves in most cases has more than offset any power loss resulting from the control technology.[30] Sale of the solid wastes captured also helps defray the investment cost.

The CO_2 Challenge for Coal

Unfortunately, a similar technological approach cannot be used to capture CO_2, because CO_2 does *not* react easily with catalysts. Stuart Dalton, Director of Generation at the Electric Power Research Institute (EPRI), explains, "Quite simply, the problem lies in the fact that anything that likes to catch CO_2 does not want to let it go. And anything that likes to let it go does not want to catch it."[31] While CO_2 can be captured using reagents such as ammonia, its low concentration in coal-plant flue gases (typically less than 15%) and relative inertness require using much more energy and additional equipment to separate out CO_2. Furthermore, there are only limited, site-specific marketable uses for CO_2 that could help defray the cost of capture. (CO_2 is used for enhanced oil-recovery applications as well as soft-drink carbonation, but current aggregate demand from these sources is estimated to be far below the potential long-term supply from capturing CO_2 emissions.) Hence, CO_2 capture poses large technical and economic challenges to the utility industry.

Furthermore, carbon-capture technology must be employed in addition to SO_2 and NOx capture, reducing plant efficiency by another nine percentage points: Efficiency falls from the 34%–43% range to the 25%–34% range, increasing the amount of fuel required to produce a kilowatt-hour of electricity. Capital costs for carbon-capturing coal plants are also about 50% higher than for coal plants that do not capture CO_2. Given the higher costs and efficiency penalty, few utilities will adopt carbon-capture technology until they are required to do so by law or by regulations that impose a sufficiently high cost on CO_2 emissions.

Our forecasts assume that the big ramp-up in capital spending on coal plants will be delayed until regulations are adopted and the research and development efforts under way on new carbon-capture technology solutions become commercially viable. Nonetheless, the utility industry is already beginning to move toward building coal plants with lower CO_2 emissions. Demonstration projects by various companies and public/private partnerships are under way in Europe, the US, Australia and China. The various technologies available are quite effective, eliminating roughly 90% of the CO_2 emissions from coal. They are, however, quite expensive.

[29] A utility's rate base, broadly defined, is its investment in plant and equipment, plus operating and working capital needed to run the business. This investment is multiplied by the allowable return to determine the return to shareholders.

[30] Retrofitting with new valves and not installing control technology would make the plants even more efficient. However, most operators will not take meaningful downtime just to replace the valves, our research shows.

[31] *Gas Turbine World*, 37, no. 3 (May–June 2007): 20

Retrofit Opportunities

Because there is so much legacy investment in coal plants, we think it likely that a portion of the existing coal fleet will be retrofitted with carbon-capture technology to leverage these sunk costs. There are several post-combustion carbon-capture technologies available today that reduce efficiency to varying degrees. In effect, these technologies divert some of the energy that would otherwise be devoted to generating electricity to capturing and compressing CO_2 (*Display 40, previous page*). Hence, the reduction in output of electricity from a retrofit, discussed above.

Some processes use liquid chemical solvents, such as chilled ammonia or methanolamine (MEA), to absorb CO_2 from flue gas. Systems using MEA have been commercially used for natural-gas processing for several decades; a chilled ammonia process is close to commercial availability at power-plant scale. These substances have high capture efficiency and can work across all pulverized-coal technologies.

But such chemical processes require an added capital cost for building a CO_2 absorption tower to separate and capture the CO_2 from the flue gas. They also reduce plant efficiency from about 39% to 29%, depending on the type of coal plant. Design studies indicate that this efficiency loss in combination with the added capital cost would increase the cost of electricity from a newly built coal-power plant by 66% (*Display 41*). Alstom, American Electric Power, McDermott and Powerspan are among the companies working to improve the technology and reduce its cost.[32] In our model, we assume that retrofit options will make economic sense in developed markets in about 2015.

Oxy-fuel combustion is a somewhat more economic alternative. Burning coal in pure oxygen, rather than in ambient air, eliminates nitrogen; the result is a flue-gas stream consisting primarily of CO_2 and water. Since the CO_2 is more concentrated, less power is needed to separate and compress it. Additionally, the volume of flue gas is smaller, so the physical plant required to separate out the CO_2 can be smaller, too. Still, the air separation unit used to supply the oxygen is an added capital cost and requires energy that reduces the plant's efficiency significantly. Adding oxy-fuel technology and capturing CO_2 would reduce the efficiency of a supercritical pulverized coal plant from about 39% to about 31%.[33]

There is optimism in the industry that there may be ways to successfully reduce the cost of oxygen production, and thereby substantially improve the economics of oxy-fuel combustion.[34] For an oxy-fuel retrofit to be effective, however, the plant's boiler would likely have to be tightly sealed to keep outside air separate from the oxygen stream during combustion. Also, in highly concentrated oxygen, coal burns too hot for traditional plant components, so plant designs would likely be modified so that CO_2 generated in the burning process could recirculate into the boiler and dilute the oxygen stream. Given efficiency data and capital costs available in design studies, we estimate that oxy-fuel would add 54% to the cost of producing a kilowatt-hour of electricity when compared with a newly built pulverized-coal plant.[35] This compares favorably to the cost estimates for chilled ammonia processes.

Display 41

Cost Estimates for Carbon Capture Vary Widely

	Levelized Cost of Electricity for Coal-Plant Types, in Various Studies						Average Cost of Electricity Increase
	MIT	GTC	AEP	GE	DOE NETL	EPRI	
Pulverized Coal, No Capture, Reference	1.00	1.00	1.00	1.00	1.00	1.00	—
Pulverized Coal, Capture	1.60	1.69	1.84	1.58	1.66	1.58	66%
Integrated Gasification Combined Cycle, No Capture	1.05	1.11	1.08	1.06	1.10	1.15	9
Integrated Gasification Combined Cycle, Capture	1.35	1.39	1.52	1.33	1.43	1.66	45

Source: American Electric Power, EPRI, Gas Turbine World, *Gasification Technology Council (GTC), GE, MIT, National Energy Technology Laboratory (NETL) and US Department of Energy (US DOE)*

32 Full Disclosure: The investment committee for AllianceBernstein Venture Fund I, L.P., a venture capital fund managed by AllianceBernstein, has approved an investment in Powerspan.

33 John Deutch, Ernest Moniz et al., *The Future of Coal* (MIT 2007)

34 One promising approach being developed by Air Products and the US DOE is the use of ion-transport membrane (ITM) technology.

35 D.J. Dillon et al., "Oxy-combustion Processes for CO_2 Capture from Advanced Supercritical PF and NGCC Power Plant," Proc. of the 7th Int'l Conference on Greenhouse Gas Control Technologies (September 2007); K. Andersson et al., eds., "An 865 MW Lignite Fired CO_2 Free Power Plant: A Technical Feasibility Study," Proc. of the 6th Int'l Conference on Greenhouse Gas Control Technologies (October 2002)

The New Plant Alternative: Coal Gasification

Expectations of more stringent environmental regulations are also leading utilities to consider gasification technology for new coal-burning electric plants. Gasification refines coal (or other fuels such as petroleum coke or biomass) to create a synthetic fuel made up mostly of hydrogen and carbon monoxide. The technology originated in the 1800s to produce so-called town gas for lighting streets and buildings, but has improved with continued use for other purposes. In the 1920s, the chemical and petrochemical industries began to use coal gasification to produce hydrogen; steam and electricity were useful by-products. Petroleum-poor countries facing trade sanctions—such as Germany during World War II and South Africa during its apartheid era—have used coal gasification to make liquid fuels. South Africa continues to turn coal into liquid fuel today. Using coal gasification primarily for electricity generation is new.

Integrated Gasification Combined Cycle (IGCC) technology is the most efficient gasification configuration for power generation. It is essentially a two-stage process. In the first stage, the coal is exposed to air or pure oxygen and steam at high temperature and pressure. A chemical reaction occurs, in which hydrogen gas and carbon monoxide (CO), as well as very small amounts of CO_2 and methane (CH_4), are released. In effect, the energy in the coal (now in the form of hydrogen) is separated from the carbon, which is mostly in the form of CO. (The CO can easily be transformed into CO_2 for capture). In the second stage, the hydrogen gas is burned to create heat to run a gas turbine that generates electricity. Excess heat from both stages of the process is used to generate steam to run a turbine that generates even more electricity.

IGCC plants capture air pollutants—including NOx, SO_2 and CO_2—at lower cost than pulverized coal plants because cleanup occurs at high pressure. They also typically consume 30%–40% less water than pulverized-coal plants, generate less solid waste and can use a wide variety of feedstocks, including high-sulfur coal, waste oils, biomass, municipal trash and natural gas. Today, it appears to be the lowest-cost carbon-capturing coal technology. Design studies indicate that the cost of electricity from a carbon-capturing IGCC plant would exceed that of a traditional coal plant by only 45%, as Display 41 also shows.

In the last 25 years, a handful of utilities and energy companies have embraced IGCC plants for power generation, or combined power and heat generation (cogeneration) plants. We estimate that there are about 18 IGCC-power plants in commercial operation globally, representing less than 1% of total coal-power plants (*Display 42, next page*). In Spain, the 318-megawatt Puertollano plant has been operating since 1998. Other power-generating IGCC plants are in operation in Japan, the US and the Netherlands. We estimate that about 80 orders for IGCC plants have been placed for completion between 2010 and 2015, but only a few of them are earmarked for power generation with carbon capture at the outset (*Display 43, page 33*).

IGCC Economics

IGCC technology has yet to take hold more broadly in the power industry because IGCC plants are more expensive to build, more complex to operate and have a history of being less reliable than pulverized-coal plants because they lack standardization and economies of scale. Carbon regulation will likely give IGCC plants a decided economic advantage, but vendors may have to offer performance guarantees.

The cost advantage of IGCC plants with carbon capture versus other carbon-capturing pulverized-coal plants stems from two primary factors: First, the gasifier emits hydrogen gas and CO (which is then converted into CO_2) at elevated pressure. This allows for smaller CO_2 separation units that cost less to build and require less energy to run than those that would be used to capture CO_2 at atmospheric pressure. Second, the flue gas stream of an IGCC, like that of an oxy-fuel plant, is not diluted by nitrogen; the higher concentration of CO_2 makes separation less costly.

Gasification has several other advantages over pulverized coal for electricity generation: IGCC-power plants with multiple gasifiers can vary output in line with demand. During a period of slack power demand, a plant operator could take one gasifier off-line or reduce the coal fed into the system to cut back syngas production without the efficiency loss typical for a traditional pulverized-coal plant. IGCC-power plants in the Netherlands and Japan have routinely operated between a 50% and 100% load, increasing and decreasing output in under an hour.

Further, hydrogen produced at a single plant can be used to cogenerate steam and produce chemicals and liquid fuels, as well as generate electric power. Gasifiers used at petrochemical plants typically produce captive electricity from waste heat to run the facility and sell excess power back to the grid. Similarly, electric plants in the future might increase their investment return by diversifying the products that they can sell.

Display 42

IGCC Technology Is Already in Use Globally

Start Year	Project Location	Project Sponsor	Gasifier Technology	Energy Feedstock	Output MW
1972*	Lünen, Germany	Kellerman	Lurgi	Coal	170
1981*	Louisiana, US	Dow	Dow	Coal	15
1984*	California, US	So. California Edison	GE	Coal	120
1987*	Louisiana, US	LGTI/Dow	Destec	Coal	208
1994	Buggenum, Netherlands	Nuon	Shell	Coal/Biomass	253
1995	Indiana, US	Cinergy	ConocoPhillips	Coal	260
1996	Florida, US	Tampa Electric	GE	Coal/Coke	260
1996	Schwarze Pumpe, Germany	SusTec	Lurgi	Petcoke†	40
1996	Kansas, US	Frontier Oil	GE	Coal/Coke	45
1996	Vresová, Czech Republic	Sokolovská Uhelná	Lurgi	Lignite/Waste	350
1997	Pernis, Netherlands	Shell	Shell	Visbreaker Tar	120
1998	Puertollano, Spain	Elcogas	Prenflo	Coal/Petcoke†	318
1999	Priolo, Italy	ISAB Energy	GE	Asphalt	510
2000	Delaware, US	Valero	GE	Petcoke†	240
2000	Sardinia, Italy	Sarlux/Enron	GE	Visbreaker Tar	550
2001	Falconara, Italy	api Energia	GE	Oil Residue	250
2001	Singapore	Exxon Chemical	GE	Ethylene Tar	180
2002	Kutch, Gujarat, India	IBIL Energy Systems	GE	Lignite	52.5
2004	Negishi, Japan	Nippon Petroleum	GE	Asphalt	350
2006	Sannazzaro, Italy	EniPower	Shell	Oil Residue	250
2006	Yankuang, China	ICCT	China OMB	Coal	72
2007	Nakoso, Japan	Clean Coal Power	Mitsubishi	Coal	220

**No longer in service*

†Petroleum coke, or petcoke, is the solid left after refining petroleum.

Source: EIA, EPRI, Gas Turbine World *and AllianceBernstein*

With CO_2 and climate-change issues firmly on the radar screen in planning decisions, regulators in many regions already appear predisposed to favor IGCC over pulverized coal. They believe that it offers the most promise for carbon capture with the least pain for rate payers. IGCC's superiority in terms of sulfur dioxide, nitrogen oxides and mercury-emissions controls without costly add-ons, and its lower water consumption, are also decided pluses.

Once the first generation of IGCC-power plants demonstrates their cost-effectiveness and reliability, we expect more utilities to follow suit. Order backlogs could develop quickly between 2012 and 2015.

IGCC Vendors

Gasification technology and expertise have traditionally resided within oil and gas firms that have themselves used it for petrochemical refining but haven't marketed the technology, for two reasons: First, the oil majors tend to be vertically integrated companies primarily focused on liquid fuels and associated products, not standardizing and improving technologies for sale to external customers. Second, there was little external demand for the technology.

This situation appears to be changing. In 2004, General Electric acquired ChevronTexaco's gasification technology so that it could improve the technology and make it applicable for large-scale use by firms that generate electricity. This business complements its gas-turbine business. GE's goal is to make IGCC as reliable as pulverized-coal

Display 43

Many IGCC and Carbon-Capture-Capable Plants Are Planned

Start Year	Project Location	Project Sponsor	Technology	Energy Feedstock	Output MW
2009	Haugesund, Norway	Naturkraft	Amine	Natural Gas	420
2009	Sardinia, Italy	ATI Sulcis	Shell IGCC	Coal	450
2010	West Virginia, US	AEP	GE IGCC	Coal	630
2010	Ohio, US	AEP	GE IGCC	Coal	630
2010	Lincolnshire, UK	E.ON	IGCC	Coal	450
2011	Indiana, US	Duke Energy	GE IGCC	Coal	630
2011	New York, US	NRG	Mitsubishi IGCC	Coal	630
2011	Eemshaven, Netherlands	Nuon	Shell IGCC	Coal/Biomass	1,200
2011	Minnesota, US	Excelsior Energy	ConocoPhillips IGCC	Coal	603
2011	Florida, US	Orlando Utilities Commission	KBR/Southern IGCC	Coal	285
2011	Teesside, UK	Centrica, Progressive	IGCC	Coal	800
2011	California, US	BP, Edison Mission Group	IGCC	Petcoke*	500
2011	Saskatchewan, Canada	SaskPower, EnCana	Oxyfuel	Lignite	300
2011	Norway (offshore)	Statoil, Shell	Amine	Natural Gas	860
2011	Oklahoma, US	Alstom, AEP	Amine	Coal	200
2011	Stanwell, Australia	Australian Government, Shell	IGCC	Coal	100
2011	Ferrybridge, UK	Scottish and Southern Energy	Amine	Coal	500
2012	Delaware, US	NRG	Mitsubishi IGCC	Coal	630
2012	Illinois, US	ERORA/Christian County Generation	GE IGCC	Coal	630
2012	Texas or Illinois, US	US DOE, industry consortium	IGCC	Coal	275
2013	Mississippi, US	Southern Company	KBR/Southern IGCC	Lignite	600
2014	Kwinana, Australia	BP, Rio Tinto	IGCC	Coal	500
2014	Western Germany	RWE	IGCC	Coal	450
2014	Mongstad, Norway	Statoil, Norwegian Government	Undecided	Natural Gas	280 power, 350 heat
2015	Schwarze Pumpe, Germany	Vattenfall	Oxy-Fuel	Lignite	300
2015	Kingsnorth, UK	E.ON	Amine	Coal	1,600
2016	Tilbury, UK	RWE	Amine	Coal	1,000

**Petroleum coke, or petcoke, is the solid left after refining petroleum.*
Source: Climate Change Capital, EIA, Gas Turbine World *and Alliance Bernstein*

power and, at most, 10% more expensive. Similarly, Siemens acquired Future Energy's gasification technology in 2006 so that it could offer turnkey solutions to the utility industry. There are six major vendors today (*Display 44, next page*).

Challenges Ahead for IGCC

Vendors are addressing several significant challenges for gasification technologies:

Modifying gas turbines hot sections so that they can burn concentrated hydrogen without compromising performance and longevity. Hydrogen burns at a higher temperature than natural gas, so the gas turbines in IGCC-power plants must be able to withstand higher temperatures than those in natural-gas combined-cycle power plants. This technical difficulty will likely be exacerbated when carbon-capturing technology is implemented: When the hydrogen gas is no longer diluted by carbon dioxide and carbon monoxide, the temperatures inside the turbine housing will increase. Heat-resistant rotor materials as well as internal cooling mechanisms for the rotor are key areas of research and development.

Creating uniform reference parameters that integrate plant subsystems in order to drive down cost.

Display 44

There Are Just a Few Vendors of IGCC Technology

Vendor	E&C Partner	Gas Turbine Partner	Application	Competitive Position
General Electric	Bechtel (US only)	General Electric	Power Generation, Chemical Production	First mover in the US utility market, offering complete package: gasification units, GE power equipment and GE financing
ConocoPhillips	Fluor	Siemens	Petroleum Refining, Chemical Production, Power Generation	Strong position in Europe; focused on refinery projects, integrating its E-gas "coker" (technology designed to work with petroleum coke as a feedstock)
Siemens	Fluor, Krupp Uhde	Siemens	Petroleum Refining, Chemical Production, Power Generation	Strong position in Europe
Shell	Krupp Uhde	Siemens	Oil Sands, Chemical Production, Liquid Fuels, Power Generation (Europe)	Strong position in Europe; specializes in polygeneration plants for its own use
Mitsubishi Heavy Industries	JGC Corporation	Mitsubishi	Petroleum Refining, Chemical Production, Power Generation	Limited power-generation exposure; focused on opportunities in Asia. Cost advantage from using air-blown technology (no need for oxy-fuel) but not carbon-capture-ready
Southern Company	Kellogg, Brown and Root	General Electric	Power Generation	Only IGCC technology designed explicitly for power generation. Cost advantage from using air-blown technology (no need for oxy-fuel) but not carbon-capture-ready

Source: AllianceBernstein

Allowing parallel maintenance of major subsystems to reduce plant downtime.

Modifying and redesigning the interior of the gasifier to withstand the increased temperature and resulting highly corrosive and abrasive environment created by the gasification of coal. The interior of today's gasifiers may have to be repaired as often as once a year. Research dollars are being devoted to developing special internal coatings and flow-path changes that will increase the durability of these surfaces.

Coal Conclusions

Today, about two dozen coal plants with carbon-capture technologies are on the drawing board. Many of these plants are close to semi-depleted oil wells where the captured CO_2 can be used for enhanced oil recovery. Most others are located near coal mines to reduce fuel-handling costs and potentially make future carbon storage low-cost and convenient.

There will be large market opportunities for both pulverized-coal and IGCC technologies that provide carbon capture. We expect companies to retrofit their largest and most efficient pulverized-coal plants and replace smaller, inefficient plants that do not justify the expenditure.

The increased capital spending on coal power needed to retrofit or replace existing coal plants to capture CO_2 emissions and to compensate for the reduction in power output at plants that are retrofitted will be massive. Although most of the equipment suppliers are huge, diverse multinationals, the market growth ahead should be big enough to increase their revenue and earnings growth meaningfully. Producers of coal and the railroads that transport it should also benefit from the elevated energy input requirements of carbon-capturing coal plants due to their much lower efficiency rates.

Capital is already beginning to flow to new coal-power technologies solutions for coal power from early-stage venture capital investors as well as mature capital-equipment firms boosting their R&D. Although coal-burning technology has not changed materially in a century, it now appears to be ripe for disruptive innovation. ■

CO_2 TRANSPORT AND STORAGE

Capture, compression, transportation and storage of CO_2 from the many large stationary sources that dot the Earth will be no easy task. It will require close government oversight and tremendous expenditures of time and money. The steps required, however, are relatively clear.

First, the CO_2 captured from large-scale stationary sources (such as coal or natural-gas power plants) has to be stored safely so that it does not escape into the atmosphere. This task is not difficult technically. The difficulty lies in its magnitude: It is huge! We expect that by 2030, almost 10 gigatonnes of CO_2 will have to be stored every year in a place where it can remain undisturbed. Between today and 2030, over 60 gigatonnes of CO_2 will be sequestered. To carry all that CO_2, mankind will have to build a new pipeline system that roughly duplicates the existing pipelines for natural gas.

Storage Sites

Several types of geologic formations have the potential to serve as CO_2 storage (or sequestration) sites, including depleted oil and gas reservoirs, unminable coal seams, mature oil wells and deep saline aquifers (*Display 45*). In addition, scientists have investigated the possibility of storing CO_2 deep in the ocean, although uncertainty about the ecological impact of doing so suggests that such a plan would not be readily accepted.

Geologic sequestration of CO_2 entails drilling a hole where the CO_2 can stay for, say, the next 1,000 years; pumping CO_2 into the hole until the storage site is sufficiently pressurized; and sealing the hole.

Display 45

Saline Aquifers Offer Most Storage Potential

Storage Type	Estimated Global Capacity (Gigatonnes CO_2)
Saline Aquifers	>10,000
Depleted Oil and Gas Fields	800–860
Enhanced Coal-Bed Methane	150
Enhanced Oil Recovery	60–120

Source: Gale, "Using Coal Seams for CO_2 Sequestration;" Geologica Belgica, *IPCC; US DOE and AllianceBernstein*

Depleted oil and gas fields provide one attractive storage option. The CO_2 injected would simply refill pockets in the Earth that have already demonstrated that they are robust enough to hold oil or gas under pressure for millions of years. As long as all the holes drilled into the site for oil or gas extraction are properly sealed—and no one starts drilling new holes—there is little reason to think that CO_2 could not be safely entombed in depleted oil fields for thousands of years.

Mature oil fields that are undergoing production declines provide a similar storage opportunity, with the added benefit that the CO_2 injected could be used to pump more oil out. This process, known as enhanced oil recovery (EOR), has been used for over 30 years in the US, which has many mature oil fields. Indeed, much of the knowledge about the injection and transport of CO_2 comes from experience in EOR. Given the attractive economic benefit, EOR operations will likely serve as the vanguard for global CO_2 sequestration.

We do not expect the oil-service firms that perform EOR to be shy about pursuing this opportunity. Today, many of these firms pay for CO_2 or extract it from natural reservoirs themselves. In the not-too-distant future, these firms may be paid to take CO_2 from power producers or chemical companies if they can do so for less than the utilities and chemical companies would have to pay to transport and bury the CO_2 themselves. All told, between depleted oil fields and enhanced oil-recovery operations, there may be capacity for up to 920 gigatonnes of CO_2, according to the IEA.

A second, distinct option is coal seams that cannot be mined, with estimated global capacity of 150 gigatonnes.[36] Like mature oil fields, these potential storage sites have an economic sweetener: in this case, capture of marketable methane. When CO_2 is pumped into a coal bed, it fills up all the small pores in the coal bed, forcing out the methane-rich gas usually there. The technology needed to perform this task has been demonstrated in field tests, but it has not yet been developed on a commercial scale. Given the high price of methane (natural gas), we expect development of this technology to attract considerable interest. In the near term, however, it is likely to be less economically attractive than carbon sequestration associated with enhanced oil recovery.

[36] John J. Gale, "Using Coal Seams for CO_2 Sequestration," *Geologica Belgica*, 7 nos. 3–4 (2004): 99–103

PLENTY OF STORAGE SPACE

Estimates of global carbon dioxide storage potential vary widely, but it is likely that there is at least enough capacity for the next century, and probably far more. We think it unlikely that lack of storage capacity will limit attempts to capture, transport and sequester carbon dioxide.

Many of the regions likely to produce the most CO_2 appear to have adequate storage. The United States and Canada, for example, have identified over 5,000 gigatonnes of sequestration space between them. Australia, another country that has taken the lead in surveying potential sequestration sites, seems to have the potential to store 700 gigatonnes of CO_2. Other regions have been less carefully investigated to date, but one estimate assigns 11,000 gigatonnes to the globe as a whole.[37]

Japan is a notable exception to this rule of plenty. Published estimates of Japanese storage capacity indicate that this earthquake-prone island nation may have less than two gigatonnes of CO_2 storage capacity. Thus, the Japanese government has expressed strong interest in ocean sequestration.

In the summer of 2007, however, Japanese investigators reported that they had discovered underground storage capacity of up to 200 gigatonnes of CO_2.[38] Their find has not yet been verified.

A great deal more work must be done before we can gain confidence in the volume and location of storage capacity. Most countries with large CO_2 emissions have begun to fund regional or national surveys. Given the worldwide ubiquity of saline aquifers, it seems likely that such surveys will tend to reveal greater storage potential than is now known. At some point in the distant future, however, CO_2 storage space may become a valuable commodity.

But even if there is ample global storage capacity, it is unlikely to be evenly distributed. In some areas, governments and business entities may bear the additional cost burden of transporting CO_2 over long distances. Thus, the availability of local storage sites may become a key consideration in siting power plants and some industrial facilities. ■

[37] James J. Dooley et al., *Global Energy Technology Strategy Addressing Climate Change: Phase 2 Findings from an International Public-Private Sponsored Research Project* (May 2007)

[38] AllianceBernstein interview with James Dooley, March 2007

Third, deep underground saline aquifers hold enormous promise, with potential capacity of over 10,000 gigatonnes of CO_2.[39] Because they are effectively useless for agriculture or human consumption, there should be little objection to their deployment for CO_2 storage. When initially injected into a saline aquifer, CO_2 is simply trapped under the rock that isolates the aquifer or within pores in the rock. Over time, however, the CO_2 should dissolve into the saltwater and eventually react with the rock to form carbonate solids. These processes are already being studied as a part of the Sleipner Project, in which CO_2 is being injected beneath the floor of the North Sea.

Fourth and last is deep ocean storage, which also holds great promise in terms of gross capacity. The proposals range from dissolving CO_2 at intermediate depths to sequestering it below 3,000 meters, where extreme pressure would keep the CO_2 in liquid form, in effect creating a lake of CO_2 on the sea floor. Environmental opposition may delay pursuit of this alternative: Some scientists believe that the roughly 300 gigatonnes of man-made CO_2 absorbed by the ocean from the atmosphere over the past 200 years has made the ocean surface significantly more acidic, decreasing pH levels by 0.1 on a scale of 1 to 14. As a result of the controversy over the impact on the oceans of deep ocean storage, we think that this option is unlikely to be pursued in the near or medium term.

[39] Dooley*, Global Energy Technology Strategy,* (see above, n. 37)

CREATING VALUE FROM NOTHING

Large-scale adoption of enhanced oil recovery (EOR) and coal-bed methane recovery could significantly increase usable global reserves and production of oil and gas. This would also increase energy security for nations with mature or abandoned oil fields and unminable coal seams.

The primary limitation on the growth of these operations today is access to usable carbon dioxide, but we expect the US to capture over 20 billion cubic feet of CO_2 a day by 2020 and over 100 billion cubic feet a day by 2030. Globally, we expect captured CO_2 to reach almost 70 billion cubic feet a day in 2020 and over 500 billion cubic feet a day by 2030.

EOR is now primarily limited to the US, where it currently accounts for roughly 4% of US daily oil output.[40] If a little less than half of the CO_2 captured and stored in the US finds its way into EOR projects, those projects could produce over 1 million barrels a day by 2020. With only 20% of the much higher volume of CO_2 that we expect to be captured and stored domestically in 2030, the US could produce an additional 3 million barrels a day. That is, EOR could increase US oil production in 2030 by 55% versus the 5.4 million barrels of oil a day that the EIA now forecasts. Cumulatively, this ramp-up would extract only one-eighth of the 80 billion barrels of discovered US light crude that the EIA estimates is amenable to EOR.

Globally, if just 15% of captured CO_2 goes into EOR projects, an additional 11 million barrels a day could be added to global production by 2030—no small portion of the roughly 85 million barrels a day now produced. In the US, EOR can extract about 7% of the total crude oil originally in the ground. If the same is true globally, EOR could allow extraction of 450 billion additional barrels of oil based on the EIA's estimate that the original global crude oil supply exceeded 6 trillion barrels. Since the EIA estimates that 1.2 trillion of the crude oil still in the ground is easily extractable, EOR could significantly add to extractable oil supplies.

A similar CO_2 flooding process can be used to extract methane from coal beds, but has not been performed at commercial scale. In this process, the CO_2 displaces the methane that frequently lurks in cracks in coal. The process is more effective, but more costly, than the depressurization processes currently used in the US, Canada and Australia to recover methane from coal beds. The costs would decline meaningfully with access to significant amounts of low-cost CO_2, which we expect by 2020.

Some 6,400 trillion cubic feet of natural gas are economically recoverable today from proven reservoirs.[41] The US Environmental Protection Agency estimates that the full development of coal beds amenable to depressurization techniques would yield an additional 3,000 trillion (and perhaps as much as 9,000) cubic feet of natural-gas reserves. Pilot-scale projects suggest that CO_2 flooding can produce 40% more natural gas from a coal bed than depressurization does.[42] Thus, over the long term, coal-bed storage of CO_2 could bolster current natural-gas reserves by as much as 65%.

The potential impact on global natural-gas supplies is significant. Current pilot projects suggest that three cubic feet of CO_2 must be injected to recover one cubic foot of methane.[43] At that rate, if 15% of the CO_2 captured in 2030 were devoted to enhanced coal-bed methane recovery, some 9.5 trillion additional cubic feet of natural gas could be extracted in 2030. That's equivalent to about 10% of annual natural-gas production today. China, with its huge coal beds, could more than double its current domestic natural-gas production in 2030 by devoting to enhanced coal-bed methane recovery less than 15% of the CO_2 we expect it to capture.

But the CO_2 transport and storage infrastructure necessary to sustain enhanced oil- and methane-recovery projects will likely take a decade to develop. Thus, in the short term we don't expect EOR or coal-bed methane recovery to disrupt current energy supply dynamics. By 2020, however, they may become disruptive. ■

[40] According to Denbury Resources, 240,000 barrels of oil a day are attributable to CO_2 flooding; the US produces 5.5 million barrels of oil a day.

[41] *BP Statistical Review of World Energy*, 2006

[42] Jack Pashin et al., *Enhanced Coalbed Methane Recovery Through Sequestration of Carbon Dioxide: Potential for a Market-Based Environmental Solution in the Black Warrior Basin of Alabama*

[43] Gale, "Using Coal Seams for CO_2 Sequestration" (see p. 35 n. 36): 99–103. Also available online at http://www.bbc.co.uk/dna/actionnetwork/A11280944

Pipeline Infrastructure

Regulation of CO_2 emissions would likely add a fourth resource consideration to site selection for new power plants: Access to a CO_2 storage facility would become important, just like access to transmission and distribution lines, water and fuel. The ideal new location for a new coal plant would have a saline-aquifer injection site nearby.

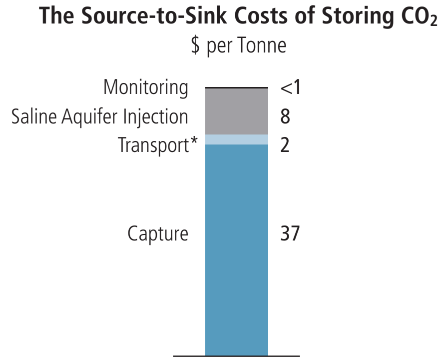
Of course, few ideal sites are likely to exist. Instead, power producers would weigh the cost of bringing three resources to a site—and taking one away. As such, we expect that power producers (or the oil-service companies that facilitate CO_2 transport and storage for them) will find a way to move the CO_2 captured from their plants to eligible injection sites. Given the volumes of CO_2 involved, this will likely happen via pipeline.

Today, the vast majority of CO_2 transport occurs in North America, which has roughly 3,500 miles of major CO_2 pipelines, transporting roughly 2 billion cubic feet of carbon dioxide a day to enhanced oil-recovery operations. We anticipate that by 2030 over 500 billion cubic feet of CO_2 will be sequestered per day worldwide, requiring a tremendous increase in pipeline infrastructure. We estimate that spending on CO_2 pipelines worldwide will exceed $15 billion a year before 2030.

Many regulatory issues must be untangled before development can proceed. It seems likely, however, that regional enhanced oil-recovery networks will eventually be folded into larger-scale national or international CO_2-sequestration superpipeline systems, as governments seek to support and regulate CO_2 transport and storage efforts.

Display 46

After Capture, Injection Is Most Costly Part of CO_2 Disposal



Assumes transport distance of less than 100 miles

Source: Heddle, Herzog and Klett, "The Economics of CO_2 Storage"; James Dooley; and AllianceBernstein

Monitoring and Liability

Governments will also likely need to offer long-term liability assurances to encourage sequestration of CO_2. The long time frames over which the CO_2 must remain trapped virtually require that governmental entities take responsibility after a reasonable period of time for the safety of private sequestration operations.

Regardless of whether the party that accepts responsibility for a CO_2 storage site is private or public, it will have to keep track of the CO_2 stored there. Oil-field service firms have expertise in measuring how much of something is beneath the surface and where it is located. These proven technologies exist and are inexpensive relative to the cost of capturing, transporting and injecting CO_2 underground (*Display 46*). ■

NUCLEAR ENERGY: THE NEW GREEN SOLUTION

We expect nuclear-energy capacity to grow significantly, with carbon-emissions policies leading to $1.1 trillion in incremental capital spending. This aggressive forecast may be startling, given the industry's contraction in the 1980s and 1990s in North America and Europe. (It grew modestly in Asia during the same period.) But over the last 10 years or so, nuclear power has proved to be safe and reliable, and has reemerged as a viable option, thanks in part to successful efforts by industry and regulators to correct the industry's problems (see "Addressing Past Problems," page 40).

Concerns over CO_2 emissions from fossil-fuel-fired plants have recast nuclear power as a "green" industry capable of meeting base-load electricity needs. Indeed, although many environmentalists rallied against nuclear energy in the 1980s, today many leading environmentalists endorse nuclear energy as a strategy to combat climate change. "Nuclear energy is the only green solution,"[44] contends James Lovelock, the geophysicist who developed the Gaia theory, on which the greenhouse effect is based. Argues Stewart Brand, a pioneer of environmentalism and former publisher of *The Whole Earth Catalog*: "Coal and carbon-loading the atmosphere are much bigger problems for the future than nuclear waste, which is relatively minor."[45]

Public sentiment also appears to be shifting. A 2006 opinion poll conducted nationwide in the US by Bisconti Research found that 68% of those surveyed were in favor of nuclear energy, compared with 49% in 1983.[46] We think that political winds will continue to shift favorably for nuclear energy as awareness of climate change grows. Even countries such as Germany that prohibit new construction are likely to revisit that stance.[47]

Most important, perhaps, nuclear power is also likely to become cheaper than any other energy source once CO_2 emissions are constrained, our research shows. While security and waste-disposal issues remain intractable problems that industry and governments will have to address, we expect nuclear power's superior economics in a carbon-constrained world to lead to a near-tripling of global capacity by 2030.

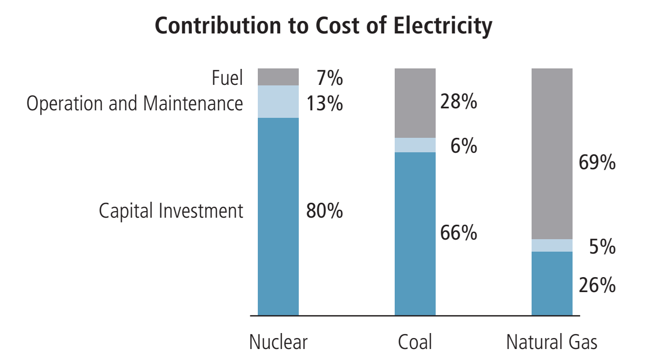
Nuclear Economics

Today, nuclear-power plants are not cost-competitive with other generating technologies. Nuclear-power plants are more expensive to build than coal and natural-gas plants, costing roughly $3,000 per kilowatt of capacity, versus $850 for natural gas and $1,900 for coal plants without carbon-capture equipment.[48] Once built, however, nuclear plants have lower operating, maintenance and fuel costs (*Display 47*).

Thus, new nuclear plants are generally more attractive investments in regulated markets, where regulators set rates to cover the substantial up-front capital costs and investment risk. Nevertheless, a few merchant generators are pushing ahead with new nuclear plants in tight power markets, such as Texas, in order to take advantage of government production subsidies and loan guarantees. Older nuclear-power plants are very attractive to operate in markets with price competition for electricity supply. In most cases, the high costs related to building the plants have largely been depreciated, so only the operating and maintenance expenses (fuel, labor, regulatory compliance, taxes and storage) must be factored into the cost of incremental production. Typically, these costs represent 15%–20% of total generation cost for such plants.

Display 47

Nuclear Power: The Most Capital-Intensive Base-Load Option



Source: IEA and AllianceBernstein

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[44] http://www.bbc.co.uk/dna/actionnetwork/A11280944

[45] *The Economist Technology Quarterly* (September 8, 2007)

[46] http://www.nei.org/filefolder/publicopinion_06-05.pdf

[47] In 1998, Germany's minority Green Party–led government enacted a law that would eventually shut down the country's 19 nuclear plants because of environmental and proliferation concerns. However, the International Energy Agency has warned that if Germany closes its nuclear-power plants it will likely be unable to meet its carbon-emissions-reduction targets. Therefore, we expect a policy change on nuclear power at some point. Extending the lives of the country's nuclear plants is among the least-costly options for reducing carbon emissions.

[48] Capital costs vary substantially by region and the specific technology employed. Figures quoted here are estimates for construction begun before 2015 in OECD member nations. Please refer to Appendix A for the assumptions that we use in our forecast.

ADDRESSING PAST PROBLEMS

Nuclear power has perhaps had more than its share of problems. Safety problems—both feared and real—as well as cost overruns nearly killed the industry in North America and much of Europe in the 1980s. The March 1979 release of the film *The China Syndrome* proved to be eerily prophetic: In the film, Jane Fonda plays a TV reporter who cajoles a nuclear engineer to blow the whistle about the strong possibility that the reactor core at the fictitious plant might trigger a meltdown that could "render an area the size of Pennsylvania permanently uninhabitable."

Twelve days after the film's release, the Three Mile Island reactor core melted down in Pennsylvania, creating a panic but no deaths. The much-worse disaster at the Chernobyl reactor in the Ukraine in 1986, in which more than 50 people died, led to abandonment of the badly contaminated cities of Pripyat and Chernobyl and stiffened public opposition to nuclear power, particularly in Europe and North America.

During the same period, the industry's earlier hopes that nuclear energy would become "too cheap to meter" were dashed by construction and permitting delays that led to the high-profile bankruptcies of the Washington Public Power Supply System and the Long Island Lighting Company in New York State, and cost overruns at the Sizewell B facility in the UK.

The structure of the industry contributed to the problem: The licensing, approval, construction and design processes were cumbersome, to say the least. In the US, operators had to apply for a construction permit, build the plant, apply for an operating license and endure a lengthy review process that frequently included substantive—and sometimes capricious—design changes by the regulator before they could open a plant. Europe and Japan had similar red tape. Ten years and billions of investment dollars could be spent before a plant generated any revenue.

Uncertainty about the cost and timing of investments put a serious damper on the nuclear-power business. The most recent nuclear reactor to open in the US was the Browns Ferry Unit 1. Shut down in 1985, it reopened in June 2007 after an additional investment of $1.8 billion. Before that, the Watts Bar I reactor in Tennessee came online in February 1996. It took 23 years to complete at a cost of $6.9 billion. A second reactor at the site, Watts Bar II, has been under construction on and off since 1973. In 2007, the Tennessee Valley Authority announced plans to complete Watts Bar II by 2013, spending $2.49 billion on top of the billions that have already been spent over the past 34 years.

In Canada, the last reactor built started operating in 1993; it ended up costing $14 billion, 250% above estimates. In the UK, the last reactor built was the Sizewell B facility, which opened in 1995. After 15 years of planning and construction, the final construction cost of $7 billion was 35% over budget.

What's Changed?

Industry experts say that neither the Three Mile Island nor the Chernobyl accident would have occurred with today's technologies and designs, which have built-in passive safety measures that use stored energy systems to cool the reactor core in the event of mechanical-system failures. Safety, per

New Nukes: The six reactors of the Ulchin nuclear-power plant in South Korea were completed between 1988 and 2005.

Photo: Areva

force, has become the industry's priority. Without demonstrating improved safety, the industry would not be reemerging today.

A more rational industry structure has also been established, along with better operating practices that make the industry far more attractive economically. In the past, a utility might have a lone nuclear plant to diversify its fleet of coal and natural-gas plants. Today, consolidated operators have multiple plants that can share best practices to improve efficiency. The number of reactor operators in the US, which has the world's largest nuclear fleet, decreased from 45 to 25 between 1995 and 2006. A few dominant global utility operators focus on nuclear power today: Constellation, Duke and Exelon in the US, British Energy in the UK; EDF in France; Korea Electric Power in South Korea; and Tokyo Electric Power and Kansai Electric Power in Japan.

System availability and efficiency have improved significantly. The hours in a year that plants generate power increased from the mid-70% range to the low-90% range over the past 20 years. Operating and maintenance costs have fallen from about 3.4 cents per kilowatt-hour in the 1990s to about 1.7 cents today.

The regulatory process has also improved. The US Nuclear Regulatory Commission has advocated best practices globally and demonstrated willingness to learn from other countries. For example, to end the time-consuming and inefficient two-step permitting process of the past, the US adopted a combined operating license (COL) and reference design approval process for new builds. The new process was modeled on the successful approval processes that Taiwan, Japan and South Korea developed during the 1980s and 1990s, when the industry was contracting in the US and much of Europe. ■

We expect the majority of the nuclear plants built in the first phase of the new investment cycle to be built by regulated, vertically integrated utilities able to win rate increases to pay for construction. In the US, they are likely to be adjacent to existing plants in the South from the Carolinas to Texas, where there is rising electricity demand and a relatively high degree of public acceptance for nuclear power. Outside the US, the capacity build-out will be more robust, particularly in South Africa and Asia. Eskom, South Africa's dominant utility, told us it plans to add 20 gigawatts of nuclear capacity by 2020. China, India, Indonesia and Vietnam are also looking to add new nuclear capacity.

We expect government support to remain essential even after strict CO_2-emissions policies give nuclear power a cost advantage. The complexity, risks, high up-front capital costs and long asset lives of nuclear-power plants mean that government incentives and guarantees are needed to drive investment to the industry. Low-interest loans, risk insurance and indemnification, production tax credits and guarantees to safeguard spent fuel in long-term repositories are frequently required. The experience in France (see "The French Way," page 42), shows how government support can be critical to the growth of nuclear energy.

Barring a major safety incident, we do not foresee long-term impediments to widespread adoption of nuclear energy, although near-term barriers remain.

Near-Term Barriers

Today, the growth of nuclear power is being constrained by several factors:

- Concerns about terrorism and nuclear proliferation risk;
- Inadequate storage options for spent fuel;
- Public opposition in certain regions;
- Reluctance of the private sector to provide financing;
- Lack of a long-dated electricity futures market for hedging long-term contracts;
- Potential for regulatory delay: The US Nuclear Regulatory Commission is bracing for a surge of applications for operating licenses in 2008 and 2009 (estimated at 30 or more). It is scrambling to hire hundreds of technical employees to review applications;
- A shortage of nuclear engineers and skilled workers; and
- Decommissioning of the aging fleet, which ties up scarce engineering and construction resources.

THE FRENCH WAY

France provides a useful case study for successful widespread deployment of nuclear energy. It also demonstrates both the critical importance of government involvement and support and the vagaries of technology licensing.

Like most of the Western world, France was crippled by the Arab oil embargo in 1973–1974. At the time, most of France's electricity came from oil-burning plants. With few fossil-fuel resources to develop, French technocrats and policymakers saw only one option: nuclear power. They launched the most comprehensive nuclear-energy program in history, installing 56 nuclear reactors between 1973 and 1985. Today, nuclear plants generate about 80% of the electricity that France consumes (the balance comes from wind, hydroelectric and coal plants). Surplus electricity is exported to other European countries.

Why has nuclear power prevailed in France while being banned in Germany, California and elsewhere? French public opinion polls have consistently shown that about two-thirds of the population is strongly in favor of nuclear power. Although the French recognize the risks associated with nuclear power, they believe the benefits are sufficient to justify its development.

French support for nuclear power may partly reflect cultural factors: Generally speaking, the French are fiercely independent and thus reluctant to rely on foreign energy sources. France does not have ample coal reserves (as Germany does) or access to cheap, nearby hydroelectric plants (as California does). In addition, France has a long tradition of large, centrally planned public works projects and a rich history and tradition in the nuclear field.

French scientists, such as Marie Curie, were pioneers of nuclear physics. French universities started programs in nuclear physics and related sciences long before US universities did. In the 1950s and 1960s, CEA, the French government atomic energy commission, sponsored nuclear research programs. The CEA first focused on gas-cooled reactors because of their favorable heat-transfer characteristics. Later, it chose to commercialize pressurized-water reactors, because they are more reliable.

Finally, the French government has effectively articulated the benefits of nuclear power for the

The market is addressing most of these issues, but terrorism, nuclear proliferation and waste storage are serious problems that still must be addressed.

Safeguarding nuclear waste is crucial for maintaining global security, particularly at facilities where spent uranium fuel is recycled or reprocessed, because spent uranium fuel can be converted into weapons-grade plutonium or enriched uranium. Thus, countries that have not signed the Nuclear Non-Proliferation Treaty are prohibited by the International Atomic Energy Agency (IAEA) from building nuclear reactors for civilian purposes. As new reactors are added in South Africa, China and the Middle East, the IAEA will have to ensure that these countries are complying with the treaty's terms and that adequate safeguards are in place. India and Pakistan are the only two countries with nuclear-power capabilities that have not signed the treaty.

Safe storage of nuclear waste is critical because spent uranium fuel is highly radioactive, posing environmental and health risks, and it takes thousands of years to decay naturally. Nuclear plants that do not recycle nuclear waste have on-site storage facilities, but operators frequently ship hazardous nuclear waste between plants for storage. If the industry doubles or triples in size, finding sufficient storage sites will become a formidable challenge.

Reprocessing significantly reduces the amount of waste that needs to be stored but adds to the cost of nuclear power. Partly because of the higher cost, reprocessing does not take place in the US and some other competitive utility markets. Countries such as France, the UK and Japan that do reprocess tend to have government support or monopoly structures. A technological breakthrough could eventually change the economics of reprocessing, but whether or not that occurs, governments around the globe need to develop and finance a secure network of permanent repositories to handle the waste from new reactors, in our view. We view storage as a political, not a technical, issue.

French economy. Indeed, France's nuclear program has become a source of national pride. Nonetheless, the French are no more eager than anyone else to have nuclear waste stored in their backyards.

French Lessons for China

The first French nuclear company, Framatome, was created in 1958, with equity participation from the Schneider Group, Empain and Westinghouse. It licensed Westinghouse technology for a modest fee. In the early 1970s, when the industry was expanding rapidly in Europe, France wanted to foster a national atomic champion. The CEA bought out Westinghouse's 45% equity stake in two steps, 30% in 1975 and 15% in 1982, when it created state-controlled Areva. Subsequently, Areva gained ownership of the technology, which it had enhanced, and stopped paying Westinghouse a licensing fee. It uses a standardized, improved version in all its plants.

China appears to be taking the French experience to heart. Like France, China has chosen pressurized-water reactors, based on Westinghouse technology. It is using local vendors for components and plans to try to obtain technology transfer to local firms. China has publicly stated that it aims to have about 40 gigawatts of nuclear energy capacity by 2020, versus eight gigawatts today.[49] Our model assumes that China will have 54 gigawatts of nuclear capacity in 2020 and 141 gigawatts in 2030, well above the Chinese government's stated goal.

Over time, we expect the Chinese government to fully exploit the competitive landscape and let the big three (Westinghouse, Areva and GE) vie for its business. We also expect China to require each to subcontract content from local Chinese companies such as Shanghai Electric and Dongfang, hoping for the opportunity to "improve" the technology and potentially change or make unnecessary the licensing terms in the future. Despite this risk, the near-term opportunity is so large that the big three players have no choice but to play the game. Areva, for example, is likely to be involved in the next phase of China's build because, as the only truly vertically integrated player, it can offer China two things that Westinghouse cannot: access to uranium sources, and reprocessing technology. GE appears to lag behind in China, but has high hopes for the market in the future. ■

49 http://www.nuclear.com/nation-by-nation/China_news.html

Storage Options

An extensive body of credible research indicates that the best long-term storage options for nuclear waste are in safeguarded repositories in stable geologic formations. Since 1999, the US has stored roughly 52,000 cubic meters of nuclear waste from military sources in the Waste Isolation Pilot Plant, located in a geologically stable salt bed in the New Mexico desert. The US is also exploring storage of spent fuel from power plants in Yucca Mountain in Nevada, but political obstacles have prevented this option from moving forward.[50] The Nuclear Regulatory Commission (NRC) has also licensed a facility in Utah, the Private Fuel Storage site, which can hold up to 17,000 cubic meters of spent fuel.

Belgium and Finland have explored storing waste in clay or hard rock formations. Even France, where public acceptance for nuclear energy is high, has had a hard time finding an adequate long-term solution acceptable to the public. Because the French reprocess their spent fuel, however, the volume to be stored is much lower than in the US: In France, the amount of nuclear waste produced by providing electricity for a family of four for 20 years could be housed inside a secure canister the size of a cigarette lighter. In 2001, Finland became the first country to approve a permanent storage site for civilian nuclear waste. Finnish waste-disposal company Posiva Oy is still researching final sites but plans to begin storing waste in crystalline rock by about 2020.[51]

State of Reprocessing Today

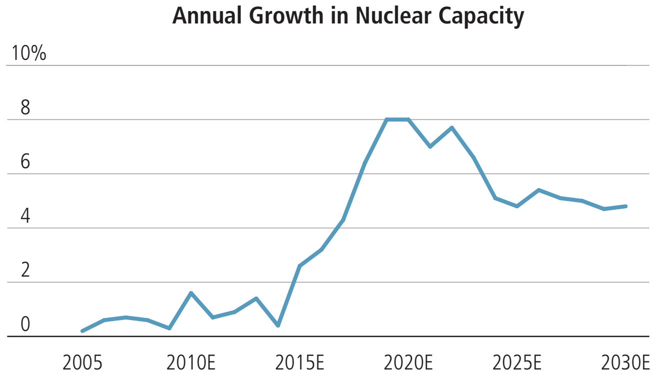
Today, reprocessing is done with government support in Russia, Japan, France and the UK, using a closed fuel-cycle process known as PUREX/MOX (Plutonium and Uranium Recovery by Extraction/Mixed Oxide). We estimate that a little more than 6,000 tonnes of

50 http://www.gao.gov/new.items/d07297r.pdf

51 http://www.ocrwm.doe.gov/factsheets/doeymp0410.shtml

Display 48

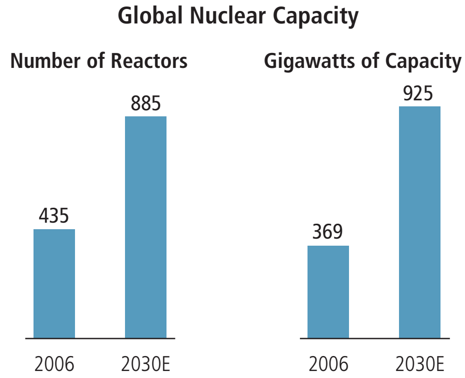
Big Gains in Nuclear Capacity Are Likely to Start in 2015



Source: AllianceBernstein

Display 49

Nuclear Power Is Poised for Significant Expansion



Source: IAEA and AllianceBernstein

spent uranium is reprocessed annually. Total uranium demand for civilian reactors in 2007 was about 32,000 tonnes.

Reprocessing could gain share as the industry expands. After initial use, a fuel rod is still 95% uranium. In addition, 1% of the spent fuel rod is plutonium created in the nuclear-power-generation process. These two valuable materials can be separated from the spent fuel's unusable radioactive waste. The uranium can be re-enriched and used as nuclear fuel. The plutonium can be diluted with depleted uranium to create a fuel known as MOX. Most pressurized-water and boiling-water nuclear reactors can replace roughly a third of their fuel with MOX without making significant design modifications.

Converting military warheads to fuel that is useful in civilian reactors is another potential fuel source for nuclear plants. The US DOE is in the process of building a MOX fuel plant in South Carolina as a safe and efficient way to convert plutonium from Cold War–weapons systems into fuel for nuclear reactors.[52] The plant is not expected to open until 2016 at the earliest. It is projected to cost $5 billion to construct.[53]

Favorable Growth Outlook

We have incorporated such identifiable obstacles as storage and nuclear-proliferation risk into our forecast for the nuclear-power industry. Our optimistic projection for net nuclear additions assumes that it will take several years to resolve some of the structural, tax, permitting and waste-disposal issues. Thus, we assume less than 1% year-on-year growth in global nuclear capacity through 2010, rising to about 8% by 2020 (*Display 48*). By 2030, we expect two and a half times as much nuclear capacity as in 2006; with 885 reactors and 925 gigawatts of capacity, compared with 435 reactors and 369 gigawatts of capacity in 2006 (*Display 49*).

One challenge to our forecast is whether the industry supply chain will be capable of handling the global surge in orders that we predict. Large vendors express concerns about potential capacity bottlenecks. In developed markets, skilled workers such as welders and pipe fitters have also been in short supply.

Nuclear Basics

Nuclear plants use the energy from splitting atoms (or, potentially, from fusing atoms) to heat water into steam; the steam drives a generator to make electricity. The basic components of a reactor are:

- The core, which includes uranium encapsulated within fuel rods;
- The moderator, usually graphite or water, which slows down neutrons produced by fission;
- The control rods, which control the speed of the chain reaction;
- The coolant, a liquid or gas that carries heat from the reactor core to a boiler to make steam for the turbines; and
- Shielding, a thick steel and concrete protective casing that prevents radiation from escaping into the environment.

[52] In September 2000, the United States and Russia signed an agreement committing each country to dispose of 34 tonnes of surplus plutonium. Separately, in 1993, the US agreed to purchase 500 tonnes of highly enriched uranium from Russia.

[53] http://savannahnow.com/node/337050

Display 50

The Global Nuclear Fleet Uses Diverse Technologies

Type	Global # of Units	GW Capacity	% Global Fleet	Main Countries	Fuel	Coolant	Moderator
Pressurized-Water Reactors	263	241.2	60%	US, France, Japan, Russia	Enriched UO_2	Water	Water
Boiling-Water Reactors	94	85.0	22	US, Japan, Sweden	Enriched UO_2	Water	Water
Pressurized-Heavy-Water Reactors	42	21.5	10	Canada	Natural UO_2	Heavy Water	Heavy water
Gas-Cooled Reactors	18	9.0	4	UK	Natural U, Enriched UO_2	CO_2	Graphite
Light Water-Cooled, Graphite-Moderated Reactors	16	11.4	4	Russia	Enriched UO_2	Water	Graphite
Fast Breeder Reactors	2	0.7	<1	France, Russia	PuO_2 and UO_2	Liquid Sodium	Graphite
Total	**435**	**368.8**	**100%**				

Data for 2006
Source: IAEA, Strategic Planning Associates and AllianceBernstein

Pressurized- and boiling-water reactors dominate the market (*Display 50*), although many other types of nuclear reactors exist. There is potential for advancements in the future, although these are at least 20 years away. In 2002, the Generation IV International Forum was formed to lay out a path for advanced "fast breeder" nuclear-power plants, which are designed to produce more fissile material than they consume. This government-sponsored consortium includes 10 nations plus the European Union. It aims to make such reactors commercially available by 2030. Another research program is the $20 billion ITER (fusion reactor) program, which aims to replicate the energy source of the sun and stars in commercial reactors. If successful, these reactors would signal the arrival of the much-anticipated "hydrogen economy," which would significantly reduce the need for uranium fuel.

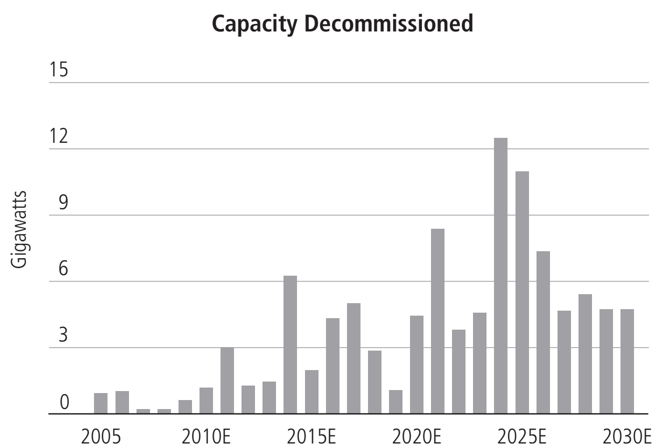
Near term, the investment opportunities in the nuclear industry are for decommissioning old plants and extending the useful life of others, as well as fuel-cycle servicing.

In the US, we estimate, at least 70 of the 104 existing units will be eligible for 20-year life extensions; the rest will be decommissioned after they reach 40. The number of safety incidents and the particular technology used are the largest determinants of which reactors will be eligible for license renewals. In Europe, safety review and operating-license procedures vary from country to country. The UK is in the process of decommissioning 10 gigawatts of nuclear capacity from its fleet of 15 advanced gas-cooled reactors, which have had a checkered operating history.

Altogether, we expect that 20%–30% of today's global fleet of 435 reactors will be decommissioned between now and 2030 (*Display 51*), providing meaningful growth opportunities for engineering and construction firms such as Bechtel, Shaw Group, URS and Fluor.

Display 51

Many Nuclear Plants Will Be Retired in the Next 20 Years



Assumes that all gas-cooled reactors are retired at 40 years and that the remaining reactors have a 70% chance of winning a 20-year license extension; those without extensions are retired at 40 years.
Source: IAEA and AllianceBernstein

WHAT ABOUT WATER?

During Europe's heat wave in the summer of 2003, 17 of France's 56 nuclear reactors were forced to operate at reduced capacity because of warming river water, and French utility EDF was forced to import expensive power to make up for the shortfall. This development raised questions about whether the technology is sufficiently reliable. Coal-power plants can face similar challenges with respect to water.

Both coal- and nuclear-power systems require enormous quantities of water to produce electricity. The hot water must be cooled in large towers or a lake, river or ocean. In both cases, the magnitude of the problem depends in part on the cooling method (water temperature can be more easily controlled in towers than in river or lake water) and on the temperature sensitivity of the reactor employed.

The French nuclear plants had a risky combination of features: a reactor type that is particularly temperature-sensitive yet cooled by river water. Most coal plants utilize cooling towers rather than lakes, rivers and oceans, making warmer temperatures less of an operating issue. Water issues are a key part of environmental permitting for new power plants, and cooling temperatures are designed to meet a region's weather patterns. We see no reason why water should be an impediment to growth for nuclear power. It could raise the cost for certain facilities if regulators deem it necessary to add additional cooling towers at reactors in regions prone to drought and extreme heat. ■

Vendors

There are three major suppliers of nuclear-power equipment globally: Westinghouse (majority-owned by Toshiba), Areva, and GE (which is allied with Hitachi) (*Display 52*). Mitsubishi Heavy Industries (MHI) is also trying to enter the market. Westinghouse has built the largest share of the existing fleet and was the first out of the gate for the next building cycle: Its AP 1000 design was approved by the US Nuclear Regulatory Commission in 2004.

All the leading vendors are in the process of commercially deploying "advanced" versions of their pressurized-water and boiling-water reactors. These next-generation reactors have passive, built-in safety systems that can stabilize and contain a nuclear reaction in the event of human error or mechanical-system failures.

We estimate that there are now 30 nuclear plants under construction: 19 in Asia, six in Russia, five in Europe and none in the US. We estimate that of this group, plus those in advanced planning, Westinghouse/Toshiba will win 40%–45% of the business, GE will win 25%–30%, Areva will win 20%–25% and the remaining 5%–10% will go to smaller players. ■

Display 52

Nuclear Energy Equipment Suppliers Are a Small Group

Component	Westinghouse Suppliers	GE Suppliers	Areva Suppliers
Fuel assemblies, reactor controls and pressure vessel equipment	Westinghouse and subsidiaries	GE (US), Hitachi (Japan and Asia)	Areva/Framatome
Pressure vessel	Doosan (China), IHI (Japan) and Japan Steel	Japan Steel, BWXT, licensees of Japan Steel	Japrotek Oy Ab (Finland), Siemens (Europe ex France), MHI (Asia)
Turbines and control equipment	Toshiba, BWXT (McDermott subsidiary) and Siemens	GE subsidiaries and Hitachi	Alstom and Siemens
Cooling towers and structures	Contractor provided	Contractor provided	Bouygues
Control room, measurement systems, computer systems	Toshiba	GE	Areva and subsidiaries
Engineering and Construction (E&C) contractor	Shaw Group, Fluor, URS	Bechtel Group (US and Europe), Hitachi (Japan and Asia)	Bouygues

Source: Strategic Planning Associates and AllianceBernstein

RENEWABLE ENERGY: HARNESSING THE POWER OF WATER, WIND AND SUN

Use of renewable-energy sources predates the use of fossil fuels by thousands of years: Water mills were reportedly used by Philo of Byzantium in the third century BC and during the Han dynasty in China, and Hero of Alexandria harnessed the wind to run machinery in the first century AD. Both wind and water mills were used widely from the sixteenth century AD until they were eclipsed by coal and, later by oil.

In the modern era, interest in renewable-energy sources has waxed and waned with the price of fossil fuels. Until the oil spikes of the 1970s, there was virtually no commercial interest in wind and solar power. Large-scale hydroelectric-power projects were generally government-subsidized public works aimed at stimulating industrial and economic growth.

In the early 1980s, US tax credits and favorable government stimulus encouraged investment in wind and solar power, but momentum died later in that decade with declines in fossil-fuel prices and the expiration of tax credits. The instability in capital flows and variability in demand for renewable energy have discouraged industry in the US and many other countries from addressing the technological challenges and building the supply chains necessary for large-scale commercial deployment.

Denmark has been the notable exception. In the early 1980s, an industry association called Danske Vindkraftverk (Danish Wind Craft Maker) persuaded the Danish Parliament's Green Party majority to establish a "feed-in" rate for wind generation. Since 1984, wind generators have been able to sell electricity to the grid on preferential terms that provide an attractive return on investment. Consequently, wind energy now represents 20% of total electricity production in Denmark.

Despite the instability in capital flows, renewable-energy technologies have improved, and today's high oil and natural-gas prices coupled with concerns about carbon emissions have once again attracted intense political and investment interest in renewable energy. However, our research shows that renewable energy's powerful advantages—inexhaustible fuel supply, low operating costs and minimal emissions of pollutants, including CO_2—are largely offset by substantial disadvantages related to initial cost, reliability, scalability and the dispatchability of the electricity generated. We expect these disadvantages to limit the long-term potential of renewable-energy sources.

We expect renewable energy (including hydroelectric power) to gain some market share over the next two decades, growing from 19% of global electric output in 2006 to 21% in 2030. While we expect wind and solar power to grow fastest, the inherent limitations to capacity utilization for both mean that huge investments in additional capacity will be required to achieve the modest growth in output we project.

Nevertheless, we focus on the prospects for wind and solar power because they appear to be the most feasible sources of renewable energy with the strongest growth prospects. We do not review hydroelectric power in depth because we believe that investment will be limited: We expect global hydroelectric-power capacity to grow, from 2.84 billion to 4.14 billion kilowatt-hours per year, or at a 1.6% compound annual growth rate, between 2006 and 2030. Most of the best hydroelectric-power sites in developed markets have already been utilized, or are too environmentally or socially sensitive to be used.[54] Hence, almost all the incremental growth will be in India, China, Brazil and other developing markets with valuable hydrological assets and large future power-generation requirements (*Display 53*).

Technological advances may someday make geothermal or tidal power more widely attractive and scalable, but they do not now appear to have potential for large-scale development. We predict that biomass power (generating energy from burning sugarcane, corn, grasses, wood

Display 53

Hydroelectric Power Is Still Growing in the Developing World

Trillion Kilowatt-Hours

	2006	2015E	2030E
US	0.27	0.28	0.28
OECD Europe	0.46	0.49	0.54
OECD Asia	0.14	0.14	0.15
China	0.37	0.67	0.79
India	0.11	0.19	0.22
Rest of World	1.49	1.72	2.16
Total	**2.84**	**3.48**	**4.14**

Source: EIA and AllianceBernstein

[54] Hydroelectric-power plants often require flooding large valleys, which may displace villages or towns and disrupt the natural ecology. Some research suggests that in tropical areas, it may result in significant greenhouse-gas emissions. Trees and other vegetation that are submerged rot, creating methane that bubbles up to the surface.

chips or garbage) will continue to play only a supplementary role as a co-firing agent with fossil fuels for electric generation. Biomass power has far lower power density than wind, solar or hydroelectric power. There is simply not enough available land to grow the vegetable matter needed to contribute significantly to electric-power supplies, without seriously disrupting food supplies or depleting forests.[55]

Wind Power

Windmills have provided local mechanical energy for thousands of years. As sixteenth-century Dutch paintings and pottery attest, windmills were once a common sight on farms in northwestern Europe. They were also used in the US for pumping water, grinding wheat into flour and sawing lumber. After the 1830s, hydro and coal power began to displace wind power because they were cheaper and more reliable: One didn't have to wait for the wind to blow to get work done.

In the 1980s, as wind technology improved, it became an important electricity source in a few markets, such as Denmark, which instituted a government-mandated preferential rate scheme for wind energy. More consistent tax credits and policy support have recently fostered greater interest in the US, Europe, India and China. Global manufacturers such as GE, Mitsubishi Heavy Industries and Siemens have entered what is now a multibillion-dollar global market.

We estimate that wind power generated 146 billion kilowatt-hours of electricity in 2006, or 4.4% of renewable electricity generated and a little less than 1% of total electricity generated globally. Global capital spending related to wind in 2006 was roughly $24 billion, and wind generation grew over 17% from 2005 to 2006. We expect it to increase at over a 12% compound annual growth rate between 2007 and 2012.

Europe is the world's largest wind market today because of favorable and consistent government policies, a better grid interconnect (including high-voltage direct-current lines between countries) and shorter distances between wind resources and demand centers. Wind generation represents a sizable share of power generation in Denmark, Germany and Spain, at about 20%, 10% and 6.5%, respectively. All three countries guarantee a fixed sales price per unit of wind-generated electricity.

In the US, more than half the states require that a certain portion of the state's electricity be provided by renewable sources over a specified period of time.[56] We expect a similar national requirement to be adopted, with wind power a primary beneficiary.

Wind Power's Pros and Cons

Wind power enjoys virtually limitless "fuel" supply, does not create nasty by-products and is now cost-competitive with some natural-gas plants on certain measures. A 2004 Stanford University study found that there is enough potential wind power to supply all the world's electricity needs.[57] Practical barriers, however, limit the use of this cheap and ample resource (*Display 54*).

Most obviously, wind strength is not consistent or easily forecasted. So-called wind farms mitigate this problem by joining groups of wind turbines together to meet an overall power-supply obligation, but unpredictability still needs to be considered.

Winds are only strong enough to be useful in some locations, and often the best locations for wind generation are far from demand centers. For example, the best wind resources in the US are in North Dakota, a large but thinly populated state with little heavy industry and no big cities. North Dakota has an estimated 138,400 megawatts of potential wind-generation capacity, enough to provide over three times the annual electricity needs of the state's 636,000 people. Nonetheless, North Dakota has only 178 megawatts of developed wind capacity today, or 1.5% of its potential.[58] The infrastructure to export wind power to demand centers in the Rocky Mountains, Midwest and West Coast has not yet been developed.

Display 54
Issues Related to Wind Power

Pros	Cons
• Most cost-competitive renewable	• Intermittent
• Ample resource	• Hard to dispatch evenly
• Regulatory support	• Lack of storage
• Clean energy source	• Inadequate transmission
• Domestic energy supply	• Aesthetics

Source: AllianceBernstein

[55] Replacing the world's coal consumption by harvesting woody biomass would require cultivating trees on about 330 million hectares, an area larger than the combined total of remaining forested land in the US and the European Union. Biomass is not a feasible strategy for meeting the world's electricity needs.

[56] http://www.eere.energy.gov/states/maps/renewable_portfolio_states.cfm

[57] http://www.stanford.edu/group/efmh/winds/Archer2004jd005462.doc

[58] http://www.awea.org/projects/northdakota.html

Equipment vendors are designing larger turbines, with more flexible blades that are capable of generating electricity at lower wind speeds, which would make more locations desirable. There are limits, however, to how much improvement can be realized.

Matching supply and demand is also a challenge. In many regions, winds tend to blow hardest at night (when demand for electricity is low) and more slowly in the afternoon (when demand peaks). Since there are not yet scalable and cost-effective ways of storing large quantities of electricity, the mismatch between supply and demand limits the potential use of this resource.

One way to surmount the obstacles created by the mismatch in the timing and location of wind-power generation relative to demand is to develop high-voltage direct current transmission lines capable of taking the electricity generated to where it is needed with relatively little line loss. Wind turbines may be sited near high-capacity interconnects capable of transmitting east/west (to take advantage of peak demand in different time zones) and north/south (to take advantages of seasonal differences in demand). Europe has fairly good interconnects; US policy is beginning to address the need for them. For more on high-voltage direct-current (HVDC) transmission lines, see page 75.

In April 2007, the Federal Energy Regulatory Commission (FERC) approved a new California Independent System Operator (ISO) transmission policy: In windy areas where the transmission infrastructure needed is now unavailable, transmission construction could be financed and built prior to wind-turbine construction, as long as the generating companies make a financial commitment to develop projects in the area.[59] This policy could help break the regional transmission logjam and encourage investment. Pacific Gas & Electric is exploring construction of a direct-current transmission line along the US West Coast to import wind power from British Columbia to its California service territory. The region's large hydroelectric resources would provide a backup source of electricity to the transmission line when wind resources were scarce.

We expect more than a fivefold increase in global production of electricity from wind between 2006 and 2030. The US and Europe have the best wind resources; thus, we expect them to remain the world's top markets, with the US gaining share over time (*Display 55*). We also expect strong growth elsewhere. Nonetheless, we expect wind to remain a minor energy source, supplying just 3% of total world electricity in 2030.

Display 55

Europe's Lead in Wind Power Will Narrow

Wind-Fleet Generation
(Billions Kilowatt-Hours)

	2006E	2015E	2020E	2030E
US	28	114	152	174
OECD Europe	94	225	244	248
OECD Asia	6	39	55	59
China	4	44	74	96
India	9	52	65	72
Rest of World	3	80	113	157
Total	**144**	**553**	**703**	**806**

Source: American Wind Energy Association, EIA, Global Wind Energy Council and AllianceBernstein

The Economics of Wind Power

The levelized cost of electricity from wind turbines is on par with some natural-gas-generating plants, particularly when the price of natural gas is high. In some prime locations, wind power can produce electricity at US$0.08–0.13 per kilowatt-hour, before including the benefit of the production tax credit of $0.018 per kilowatt-hour that now exists in the US. Wind power would become even more competitively priced if the prices of natural-gas and coal power rise to reflect the cost of carbon emissions.

But calculations of the levelized cost of electricity typically do not include the cost of providing backup power when the wind does not blow (or, in the case of solar power, when the sun does not shine). They also do not include the added cost of managing the flow into and out of the electric grid created by the intermittent nature of wind power, or the cost of additional transmission required to bring wind power to market from often remote locations.

Nonetheless, there has been significant investment in wind power that we expect will continue in the near to medium term, because of political support and the availability of attractive sites. We predict that annual global capital spending on wind power will average

[59] http://www.ferc.gov/news/statements-speeches/kelliher/2007/04-19-07-kelliher-E-5.asp

Display 56

Vestas Leads in Wind Energy

2006			
Company	**Market Share**	**Revenues**	**Country**
Vestas	~28%	$5.1 billion	Denmark
GE Wind	~15	~$3.8 billion	US
Gamesa	~15	$3.2 billion	Spain
Enercon	~15	private	Germany
Suzlon	<10	~$1.0 billion	India
Siemens	<10	~$1.0 billion	Germany

Source: BTM Consult, MAKE Consulting and AllianceBernstein

about US$25 billion from 2008 to 2020. Its share of total renewable electricity production will increase from 4.4% in 2006 to 13% in 2030, while its share of total global power generation goes from less than 1% to 3%. Longer term, we expect considerations of the full economic cost to slow investment in this power source.

Vestas, GE Wind, Gamesa and Enercon are the world's leading vendors of wind-power equipment, with almost 75% of global market share (*Display 56*). Most subcomponent suppliers are European, reflecting Europe's historical dominance of the wind-power market. We expect the supply chain to globalize to satisfy demand growth from Asia. Wind turbines are very large: Many are 80 meters tall, have 40-meter-long blades and weigh as much as 150 tonnes fully assembled. Their size and weight make them complex and costly to transport and erect, so subassembly is likely to be done on site. Today, critical components such as gearboxes, generators and bearings are in tight supply, but we expect market conditions to become more accommodating in one to three years.

Solar Energy

Solar energy offers vast potential: The sun radiates enough energy every day to supply all the world's energy needs 10,000 times over. But there is no sunshine at night and too little on cloudy days, and solar energy cannot yet be efficiently converted into electricity. Thus, solar power is not now cost-competitive with fossil-fuel sources.

Photovoltaic cell technology, typically installed on individual building rooftops, has been around for over 50 years.[60] It now includes a diverse array of technologies (*Display 57*). Concentrated solar-power systems, which often employ completely different technologies to produce electricity at utility scale, were first deployed over 20 years ago. Although both types of solar-energy technologies continue to be improved, their supply and sales channels are still undeveloped relative to wind and hydroelectric power. Thus, both types of solar power have lower economies of scale and higher costs than the more mature wind- and hydroelectric-power markets.

Display 57

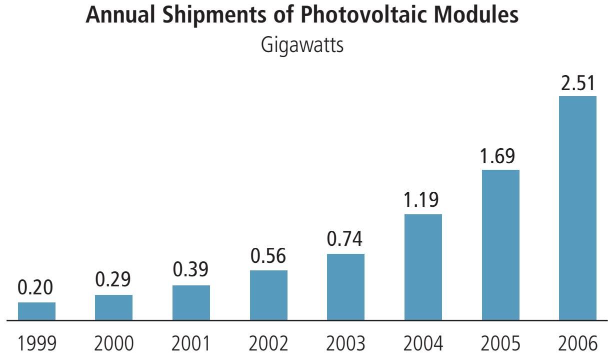
There Are Many Photovoltaic Technologies

Solar Technology	Production Share 2006E (%)	Conversion Efficiency (%)	Manufacturing Cost* ($/Watt)	Advantages/Disadvantages
Multicrystalline Silicon	56	12–14	$2.50 to $3.20	Dominant market share because it has best balance between cost and efficiency; dependent on silicon feedstock that is now in short supply
Monocrystalline Silicon	29	15–18	$2.50 to $3.45	Highly efficient but expensive to manufacture; dependent on silicon feedstock that is now in short supply
Thin-Film Materials	6	6–10	$1.20 to $2.00	Low production costs, easy to integrate with building products and not dependent on silicon supply; lower efficiency, potentially hazardous waste materials
HIT (Heterojunction with Intrinsic Thin Layer)	5	18–22	$2.75 to $3.75	Single thin silicon wafers are surrounded by amorphous silicon. Highly efficient; high manufacturing cost
Noncrystalline (Amorphous) Silicon	4	4–7	$1.75 to $2.35	Absorbs light easily; low efficiency and hard to scale

**Excludes the cost of installation and equipment for connecting to the electricity grid*
Source: EIA and AllianceBernstein

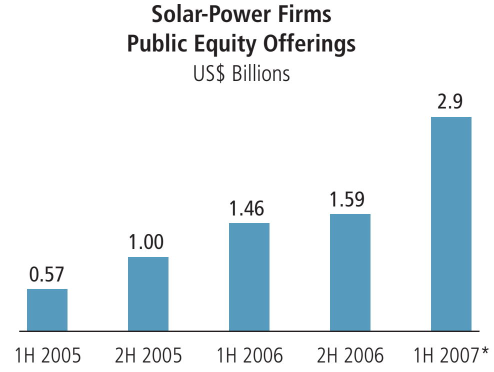
[60] In 1954, Bell Labs unveiled a solar battery that converted light into electricity.

Display 58
Solar Power's Growth Appears Attractive



Source: Photon Consulting and AllianceBernstein

Display 59
Capital Is Pouring into Solar Power



**Excludes $358 million raised in July 2007*
Source: Citi Global Markets and AllianceBernstein

Like wind power, solar power attracted capital when fossil-fuel prices were high and lost its allure when prices for fossil fuels fell. Worldwide, less than 50 megawatts of photovoltaic cells were shipped per year until the early 1990s, when the Japanese and German governments created incentives. Other countries—particularly Spain, South Korea and the US—followed suit soon thereafter.

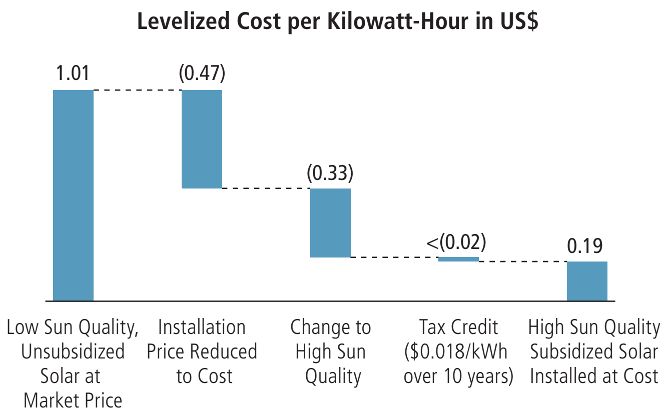
The solar industry has benefited recently from spectacular policy-driven growth: Shipment of photovoltaic modules increased 12-fold between 1999 and 2006 (*Display 58*). We estimate that by the end of 2007, installed solar capacity worldwide will reach about 10 gigawatts. Financial capital has poured into capture this growth potential: Over the last two and a half years, about 20 solar-power-related firms have raised a total of $8 billion from new stock offerings (*Display 59*), while early-stage solar companies have garnered about $300 million in venture capital funds. We think that the speculative interest is becoming bubble-like, particularly given that industry fundamentals depend on government subsidies and political support.

Solar-Power Economics

Without subsidies, solar energy is not cost-competitive with other sources of electricity. The levelized cost of electricity for photovoltaic solar power varies widely. We estimate that in a relatively sun-poor location, such as Berlin, solar power would cost US$1.01 per kilowatt-hour at current installation prices. In a high-sun location, such as Tucson, Arizona, solar power from a unit installed at cost with the benefit of a subsidy of $0.018 per kilowatt-hour could cost as little as $0.19 per kilowatt-hour (*Display 60*). The levelized cost of power, however, does not include the added cost of providing a source of backup power or the grid-management costs related to solar power's intermittent nature, as we noted in the wind-power section.

The cost of installing a photovoltaic cell on a home is only competitive with the cost of purchasing electricity from the grid in a handful of expensive electricity markets, most notably Japan and California, during periods of peak pricing. We estimate that solar-electricity prices, excluding subsidies, would need to decline by more than 50% in sunny regions and by more than 75% in less sunny regions to be competitive with the fully delivered retail cost of electricity.

Display 60
Sun Quality and Installation Drive High Cost of Solar Power



Low sun quality is Berlin, which has 2.96 hours of peak sunlight a day on average over the course of a year. High sun quality is Tucson, Arizona, which has 6.59 hours of peak sunlight a day on average.
Source: NREL and AllianceBernstein

The sand-to-rooftop cost of producing and installing photovoltaic cell modules is less than $3.50 per watt today, with the cost per kilowatt-hour dependent on the number of hours of direct sunlight. The fully delivered price for consumers, however, is about $7.50 per watt, because of the high markup throughout the value chain, particularly in silicon raw material and in installation.

We believe that the fully delivered cost of a photovoltaic cell is likely to fall to $3.50 a watt between 2012 and 2015. Economy-of-scale benefits, best-in-class manufacturing practices, a better silicon supply-and-demand balance, efficiency gains and a more developed network of installers should drive down costs substantially. If retail electricity prices rise because of carbon-capture costs, as we expect, solar power may become cost-competitive by the end of the next decade in areas with ample strong sunshine.

SOLAR MODULES at the Blijdorp Zoo in Rotterdam have a peak capacity of 500 kilowatts per hour. But cloudy Rotterdam gets fewer hours of peak sun per year than Nome, Alaska. Output from the zoo's installation is likely to average about 63 kilowatts per hour.

Photo: http://www.iea-pvps.org

Photovoltaic Industry Fundamentals

The solar industry's rapid growth caught suppliers of polysilicon off guard. Demand exceeds supply for high-purity polycrystalline-grade silicon, the basic feedstock required to make photovoltaic solar cells. As a result, prepaid pricing for silicon feedstock has soared as high as $100 per kilogram in 2007; spot prices have exceeded $300 per kilogram. In 2001 and 2002, by contrast, spot prices were around $20 per kilogram.

New entrants, particularly Chinese manufacturers, are rapidly adding silicon production capacity to exploit today's supply-and-demand imbalance and the strong price signal from the spot and contract markets.

While silicon supply directed at the solar industry is projected to grow at about a 40% rate through 2010, the industry is not expected to build massive excess capacity in the very near term because demand will continue to be propelled by government subsidies and requirements that renewable energy constitute at least a certain share of electric capacity. Also, refining capacity at existing plants typically takes two to three years to build and costs anywhere from $200 million to $500 million. Furthermore, three of the six dominant polysilicon manufacturers (Hemlock, Tokuyama and Mitsubishi) are likely to be cautious. These companies vividly remember steep downturns over the past 30 years and understand that capacity buildups can lead to depressed pricing and profits.

We estimate that the cash breakeven cost for additions to refining capacity today is about $25 per kilogram for traditional "Siemens" refining technology and about $18–$20 per kilogram for the fluidized-bed reactors being deployed by companies such as REC.[61]

Silicon Feedstocks

The starting material for most photovoltaic cells is silicon dioxide, the most prevalent element in the Earth's crust except for oxygen. Silicon dioxide makes up about a third of the Earth's crust, mostly as a component of sand and rock (such as quartz). Thus, supply of the raw material is not an issue over any time horizon. To be useful to the solar or computer-chip industries, however, silicon must be purified into polycrystalline silicon in an expensive and energy-intensive multistep process.

High-quality silicon dioxide (SiO_2) is reduced to metallurgical-grade silicon (MG-Si) in a blast furnace. Over a million tonnes of MG-Si are produced globally every year. Most of it is used to make aluminum alloys, steel and the silicones used as sealants and in various household products. A small fraction is further refined to produce high-purity material for the semiconductor and

[61] REC Silicon in Moses Lake, Washington, is developing a thermal silane (SiH_4) decomposition process in a fluidized-bed reactor. Its cost advantage over the traditional Siemens process comes from using less energy and allowing continuous processing, rather than batch processing.

photovoltaic-cell industries. The MG-Si is first made to react with water-free hydrochloric acid to form trichlorosilane ($SiHCl_3$), a liquid with a very low boiling point (around 32°C). Then, the $SiHCl_3$ is made to react with hydrogen at 1100°C for eight to 12 days in a very large vacuum chamber to produce pure silicon vapor and hydrochloric acid. This process, developed by Siemens in the 1960s, dominates industry practice.

The silicon vapor is condensed and collected on small-diameter polysilicon rods, which are used to create ingots of up to 20 centimeters in diameter. Polysilicon ingots are composed of very small regions of silicon atoms perfectly arranged in crystalline order throughout the material, rather than in one large crystal. Some of the polysilicon material is used to make polysilicon solar cells directly: the so-called polysilicon or multicrystalline solar cell. Some of it is processed into single-crystalline or monocrystalline wafers to make slightly more efficient monocrystalline solar cells. A further refining step is needed to make the material fit for use in the semiconductor industry.

Today, the semiconductor industry consumes all the highest purity material required for integrated circuits, and the solar cell industry takes much of the rest.

The Solar PV Value Chain

There are five steps in the process of making raw silicon into a fully assembled module ready for electricity production:

- **Silicon production:** a chemical-refining process that yields ingots, which are blocks of silicon material
- **Wafer production:** cutting the ingots into thin slices
- **Cell production:** transforming a raw silicon wafer into a cell capable of converting photons into electricity
- **Module assembly:** joining groups of cells together into a unit
- **Installation:** grouping modules together on a rooftop in a complete photovoltaic system that includes all other required equipment

There are a few dominant polysilicon manufacturers today: Hemlock, REC, Tokuyama, Wacker, MEMC and Mitsubishi. The rest of the solar-supply chain is highly fragmented, with many players competing in each part of the production and assembly process. Production of photovoltaic wafers and cells from polysilicon rods requires advanced equipment and process know-how. Thus, the wafer and cell stages of the business have higher barriers to entry than module assembly, distribution or installation.

Cell producers have significant leverage in the solar-supply chain, since it is a highly value-added process. They will likely play a significant role in reducing the cost of solar power. The key metric is reducing the amount of silicon needed per watt of power produced. As cell manufacturers work to increase efficiencies and minimize defects, they require thinner silicon wafers that meet ever-tighter design specifications. Our research shows that there are still vast differences in wafer quality: Wafers made by US, German and Japanese producers tend to be far superior to those made by newer Chinese producers. The five largest solar wafer manufacturers in 2006 were REC, SolarWorld, SCHOTT Solar, PV Crystalox and the Sumitomo Corporation.

Solar cell producers are actively pursuing more efficient production techniques. They are focusing on increasing throughput and line runs, minimizing cell breakage, reaping economies of scale, improving processes that increase cell efficiency and reducing wafer thickness. The top five global cell producers in 2006 were Sharp, Q-Cells, Motech, Kyocera and Mitsubishi Electric.

Promising Thin-Film Technologies

The polysilicon-supply shortage is generating interest in other technologies for converting solar energy into electricity—most notably, thin films made of amorphous (noncrystalline) silicon and/or of compounds such as gallium arsenide (GaAs), cadmium telluride (CdTe), copper indium diselenide ($CuInSe_2$) and copper indium gallium diselenide ($CuIn_{1-x}Ga_xSe_2$).

Like photovoltaic cell modules, thin-film modules are typically installed on rooftops so that individual buildings can generate their own electricity supply. The thin films, however, use layers of semiconductor material only one to 10 microns thick. While still immature, they offer significant potential for increasing the efficiency of converting thermal energy into electricity. The theoretical efficiency of thin films is 15%–18%, compared with the 6%–10% efficiency achieved today. If technological improvements bring thin films closer to their theoretical efficiency, they would be very attractive because they are so much cheaper to produce than crystalline silicon. Crystalline silicon is much closer to its theoretical limit of 27% and expensive to produce.

Some thin-film technologies (such as amorphous silicon) are flexible. This makes them easier to integrate into residential and commercial building materials, such as roofs and shingles, than polysilicon-based modules. Other thin-film technologies are better at converting low-angle and diffuse sunlight into electricity, so they can generate 10%–15% more kilowatt-hours per watt of capacity than traditional crystalline silicon modules. For example, calculators powered by amorphous silicon work fairly well in dimly lit rooms.

Concentrated Solar Power

Concentrated solar-power (CSP) plants typically have generating capacity of between 50 and 500 megawatts and are economically attractive in areas with vast amounts of intense sunlight and available land, such as North Africa or the Nevada desert. Large installations can require up to 10 square miles of land. These systems were first deployed in the 1980s but became uncompetitive in the 1990s when natural-gas prices collapsed.

Today, concentrated solar power is experiencing a renaissance. It has a much lower cost than distributed solar module systems because the plants are constructed of off-the-shelf commodity components such as glass, steel and concrete and use traditional utility power-generation equipment. We estimate that concentrated solar power can produce electricity for as little as $0.13 per kilowatt-hour.[62] Efficiencies can reach 40% or more in the best locations.

Worldwide, there is about 450 megawatts of installed concentrated solar power. Most of it is in the US; the rest is in Spain, Portugal and Israel. The current pipeline of projects is extremely active. In July 2007, Pacific Gas & Electric announced that it would purchase solar power from a 553-megawatt concentrated solar-power plant in the Mojave Dessert starting in 2011. We expect the major markets to be in the US, Algeria, China, Egypt, Greece, India, Italy, Mexico and South Africa.

There are several CSP plant configurations:

Parabolic-trough systems use huge clusters of rectangular U-shaped adjustable mirrors that track the sun's rays and focus the energy on an oil-filled pipe. The sun's energy heats the oil, which in turn heats water in a conventional boiler.

Dish/engine systems use a mirrored dish that channels the sun's rays onto a receiver, which transfers heat to fluid inside a closed-cycle Stirling engine[63] to generate power.

Tower systems have a large field of mirrors that concentrate sunlight to heat molten salt inside a tower-top receiver; the salt's heat creates steam for a generator. Since molten salt retains heat efficiently, the heat can be stored for days before being converted into electricity.[64]

Concentrated photovoltaic (CPV) systems use mirrors or lenses to focus light from a relatively broad collection area onto a much smaller area of polysilicon-based active semiconductor cell material. CPV systems must be pointed directly at the sun because they work by focusing sunlight onto a targeted area. Therefore, they require trackers that follow the sun's trajectory throughout the day. Not surprisingly, interest in this technology has surged since the polysilicon shortage began. CPV systems use a modified version of the triple-junction cell, stacked layers of semiconductor compound materials that capture more of the solar spectrum. Such technologies have proven efficiencies of 40% or more under moderate concentration of terrestrial sunlight.[65] Proponents contend that CPV will be cost-competitive with grid power for large-scale installations in solar fields because they use as little as 0.1% of the semiconductor material per watt produced as a conventional silicon photovoltaic cell. Companies such as Spectrolab (owned by Boeing), EMCORE, SolFocus and Amonix (which is privately owned) are focusing on this opportunity.

CSP plants can be used in tandem with combined-cycle natural-gas plants. In these plants, heat from the sun is used to preheat water that exhaust gases from the gas turbine will boil. Such a system could get significantly more work out of natural gas, operating at an efficiency of about 70%, compared with the 50%–60% of a standard natural-gas plant.

One concern for CSP is the loss of optical performance over a period of years. Accumulated contamination or

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[62] At 40% capacity factor, unsubsidized

[63] A Stirling engine is an external-combustion engine that uses heat to expand trapped gases to drive a piston that operates an alternator to generate electricity, and cools to contract again. Concentrated solar energy can be used in place of an external-combustion source to provide the heat required; a combination of convective and radiative cooling can be used to provide the cooling required. Stirling engines are more costly than internal-combustion engines but potentially more efficient. They are also quiet and nonpolluting.

[64] http://www.nrel.gov/learning/re_csp.html

[65] http://www.nrel.gov/news/press/2007/524.html

wind-driven particle erosion can reduce the reflectivity of the mirror surface or scatter the lens. Because there are a relatively limited number of CSP plants installed worldwide, it is too early to know how these issues may affect plant availability or the economics of utility-scale developers using the technology.

Although CSP may be scalable, we expect the technology to only make sense as a stand-alone source of power in a limited number of locations with intense sunlight.

Opportunities for Improvement

There are many opportunities for improvement in the relatively immature solar industry, including more efficient technologies, use of lower-cost materials and increasing manufacturing scale to improve yields. Improved distribution and installation of solar modules could also help a great deal: Today, installation costs represent about half the total cost of power from solar modules, because the end market is fragmented and the customer base is primarily residential.

While it is too early to determine what long-term business models will prevail, solar modules may eventually be integrated into building materials and sold through well-established distribution networks like those that now sell and install furnaces, air conditioners and water heaters.

At some point, if the economics sufficiently improve, electric utilities may decide to own and service solar-power modules. Utilities in the US and Europe now simply sign agreements to purchase power from developers of concentrated solar-power systems such as Acciona Energy, Stirling Energy Systems and Solel Solar Systems in order to comply with renewable portfolio obligations imposed by regulators. ■

REGULATION

Regulation will be crucial to greenhouse-gas abatement. Greenhouse-gas emissions, like other pollutants, are an externality: a negative consequence of self-interested action that imposes severe costs on third parties. Because the steps necessary to reduce these externalities are costly, it is unreasonable to expect individuals, businesses or other entities to undertake them voluntarily. Indeed, businesses trying to be "good citizens" would likely have to sell at uncompetitive high prices or earn unacceptably low profits, unless their competitors volunteered to be good citizens, too.[66]

Regulation can take several different forms, and the global regulatory framework enshrined in the 1997 Kyoto Protocol generally leaves it up to nations to decide how to meet their emissions-reduction targets.[67] Some countries (and local governments within them) may simply ban emissions of certain greenhouse gases or require specific abatement technologies, imposing fines for noncompliance. A larger number of countries are likely to limit emissions while applying more flexible, market-based approaches, such as cap-and-trade programs, purchases of carbon offsets, carbon taxes and strict efficiency standards.

We expect global coordination to limit emissions within the next five years, probably coinciding with the end of the first phase of the Kyoto Protocol in 2012. Climate-change policy is likely to become interwoven with energy-security policy, broadly defined as government efforts to maintain a stable supply of energy. To make a difference in stabilizing emissions, a global climate-change treaty would have to include the world's major emitters, most notably the US and China. We think it will.

While a precise policy prescription is beyond the scope of this study, our research suggests that the best policy would combine elements of a carbon tax, emissions permits (or rights) trading and carbon-intensity standards to encourage efficiency. Such measures would encourage technological solutions and least-cost abatement, and would provide maximum compliance flexibility without undue wealth transfers. Emissions-reduction targets would be more effective if they do not impose an unfair burden or confer unfair benefits on any one industry, technology or subset of consumers.

To discourage noncompliance, greenhouse-gas emissions policies could be intertwined with other strategically important policies, such as national security and global trade agreements. For example, a Chinese steel producer that fails to comply with its emissions-reduction obligation might see its revenues reduced by a carbon tax imposed on exports to emissions-compliant countries.

In this section, we review the potential approaches and how they have worked so far. We also review the political outlook for their adoption.

Taxing Carbon Emissions

Many economists believe that taxing carbon emissions would be the most effective policy for regulating climate change because, much like a value-added tax, it would be relatively straightforward to institute and could be applied to the whole economy without creating distortions.[68] But economists do not run for political office; raising taxes is very difficult in democracies. To gain public support, the perceived benefits would have to outweigh the costs, and the public would have to be confident that the tax proceeds would be used effectively by the government to fund and commercialize low-emissions technologies that might not otherwise be developed by market entities. This has already happened in a few environmentally minded European countries, notably Sweden, Finland, Norway and the Netherlands. Despite the recent shift in sentiment regarding the need to reduce carbon emissions, we believe there is little public appetite for a carbon tax in the US.

A number of countries have been tackling carbon emissions indirectly, as part of a broader taxation scheme. European countries have long used taxes on things that are bad for the environment as an instrument to raise

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[66] Some companies are making efforts to abate CO_2 emissions in order to burnish their company image. UK retailer Tesco, for example, has begun displaying information about the amount of CO_2 emissions generated in the production of some of the 70,000 products that it sells. This allows its consumers to make purchasing decisions with climate change in mind, while costing the company relatively little.

[67] Under the Kyoto Protocol, Annex-1 signatories (developed countries) are required to reduce their emissions by an agreed-upon amount relative to a 1990 baseline in the 2008–2012 commitment period. Countries unlikely to meet their targets are allowed to use so-called flexibility mechanisms, such as purchasing carbon offsets from others, to avoid a noncompliance penalty in the second compliance period, 2012–2016.

[68] Several well-known economists, including Greg Mankiw, professor of economics at Harvard University and former chair of President Bush's Council of Economic Advisors, believe that Pigovian taxes would be a good solution for climate change. Pigovian taxes are named for economist Arthur Pigou (1877–1959), who developed the concept of market externalities. They are designed to correct situations where market forces are out of line with public interest. Climate change is a great example of such market failures. Without imposing a cost on carbon emissions, there is no economic incentive to reduce emissions. http://gregmankiw.blogspot.com/2006/04/comeback-for-pigou.html

THE PATH TO GREENHOUSE-GAS REGULATION

The Kyoto Protocol on Climate Change, hammered out in 1997, went into effect in 2005 with 163 signatory nations. It included every developed nation except for Australia and, crucially, the US. The results, so far, have been limited: Even Japan and EU countries, which are deeply committed to reducing greenhouse-gas emissions, are behind schedule in meeting their self-imposed targets.

Clearly, getting the world to cut greenhouse-gas emissions is challenging, but we think that it is not impossible. Global efforts to reduce ozone-depleting emissions have worked: The hole in the ozone layer over Antarctica has been shrinking.

Our model assumes that a new global agreement on climate change will be reached between 2008 and 2012, with full compliance phased in by 2016, as Phase II of the original Kyoto Protocol expires. We also assumed that the agreement will have support from the world's two largest carbon-emitting nations, the United States and China.

Given recent political developments and court decisions, California's aggressive climate-change abatement goals and plans for a regional cap-and-trade system in the Northeast, we expect the US to join the global carbon-trading effort in the post-Kyoto period after 2012. Our optimism on this score is strengthened by the commitment expressed by many US business leaders we interviewed, who said they wanted to learn from the shortcomings of the Kyoto Protocol and the EU's Emissions Trading Scheme (ETS) to shape a better carbon-trading policy in the US.

China also appears to be taking emissions reduction seriously. The government is putting equal emphasis on mitigation and adaptation. Its "harmonious society" doctrine calls for sustainable development and recognizes that it must decouple economic growth from emissions growth. Accordingly, China is targeting a 20% reduction in energy consumption per unit of GDP by 2010.[69] ■

[69] China's National Climate Change Programme (June 2007): 26

revenues in national budgets and to discourage the use of such products. For the past several years, energy taxes have accounted for about 6.5% of total EU tax receipts and 1.5%–3% of total US tax receipts.[70] Among these taxes are excise duties on mineral oils, duties on electricity and taxes on coal, gasoline and diesel fuel.

Cap and Trade: The Theory

Cap-and-trade programs have emerged over the last 15 years as effective ways to curb air pollutants. Such programs are based on the concept of tradable property rights and permits.[71] Theoretically, they motivate businesses and households to reduce emissions in the least costly way, minimize the total social cost of reducing emissions and rationalize the cost to particular entities.

Typically, a government establishes a cap on total emissions within a jurisdiction every few years, allocating emissions credits by auction or giving them out free to existing emitters (or both). The credits become a commodity that, like pork bellies, oil or Treasury futures, can be valued and traded. When well designed, such programs encourage emitters to weigh the marginal cost of installing pollution-control technology versus the market price of buying or selling emissions permits. If it would cost a utility $30 per tonne to reduce emissions from its plants but only $15 per tonne to buy emissions permits, it would buy the permits. If it would cost the utility only $10 per tonne to reduce emissions and it could sell its permits for $15, it would reduce emissions and sell its permits.

How the emissions rights are administered and granted is critically important in determining who wins and who loses. Cap-and-trade programs create value for commodities—such as sulfur dioxide (SO_2) and CO_2 credits—where none before existed. How the allowances are allocated determines who receives the value: consumers, producers or the government, or some subset of one or more of them. In an auction, the government receives the

[70] Eurostat and Congressional Budget Office (CBO)

[71] The concept of tradable property rights was pioneered by economist Ronald Coase. In 1960, Coase proposed a marketized solution in a paper called "The Problem of Social Cost," which eventually became the Coase Theorem, earning him a Nobel Prize. http://www.sfu.ca/~allen/CoaseJLE1960.pdf

value, just as it does when licensing parts of the wireless spectrum. If the government uses the proceeds to lower income tax or sales tax, or funnels the proceeds into R&D for clean energy, the value is broadly distributed. If the government grants free allowances to industry, industry receives the value. Sometimes, preexisting emitters are granted the free allowances to compensate them for the decline in profitability that the cap would otherwise incur. If the value of the grants exceeds the decline in profitability, these companies may receive a windfall. In short, cap-and-trade programs can transfer a substantial amount of money from those who bear the costs of those allowances (generally the consumer) to those who get the value of them. Thus, their design can be politically sensitive.

Cap-and-trade programs can include price caps, known as "safety valves," which protect emitters from a sharp spike in the market price of pollution rights. Safety valves are essentially a promise by the government to sell additional permits above a set price if the market price of the permits soars, capping the allowance price.

Because triggering the safety valve allows additional emissions, the safety valve must be treated as a loan, not a grant, to maintain a system's effectiveness as an emissions-abatement policy. Companies that buy extra permits to emit, say, 100 tonnes more carbon in one year would be allowed to buy permits for 100 fewer tonnes the next year. The price cap would also have to be reasonably close to the marginal cost of investing in carbon-abatement technology to maintain the system's effectiveness.

Cap-and-trade programs have worked successfully: Most notably, a US cap-and-trade program for sulfur dioxide (SO_2), instituted in 1990, is widely credited as a significant contributor to the reduction in acid rain in the US. It should easily achieve its goal of reducing emissions to 8.95 million tons by 2010, 50% below the 1980 baseline. In its Acid Rain Program, the US Environmental Protection Agency (EPA) set a cap on SO_2 emissions for each coal-burning-power plant in the US. It let utilities and other emitters choose whether to install scrubbers, burn low-sulfur coal, save allowances for future use or sale, or buy credits for emissions beyond their caps. The price signal from the SO_2 credits—determined by supply and demand in the emissions market—helped the regulated entities decide which path to take.

Cap and Trade: The EU Experience

In 2005, the EU Emissions Trading Scheme (ETS) became the world's first carbon-trading market aimed at reducing CO_2 emissions. It was structured similarly to the US program for SO_2. Under the ETS, regulated entities—primarily utilities and cement factories[72]—were assigned a baseline allocation of carbon emissions and required to reduce emissions from that level over a specific period of time. The EU ETS experiment proves that a carbon-trading market can work: Trading activity exceeded $30 billion in 2006 and is expected to reach $100 billion by 2010.[73] While these trading volumes are still small relative to volumes for other global commodities, they are nontrivial for such a new market, and the growth rate is notable. Nonetheless, several design flaws have limited the effectiveness of the EU ETS's.

The most significant technical flaw was that regulated entities were allowed to set their baseline allocations based on preliminary estimates of recent emissions that were neither reported nor verified. Eventually, it became clear that these entities had come up with high assessments that made it fairly easy for them to comply with emissions-reduction requirements. Some companies gamed the system, running coal-fired plants at a loss in order to boost their baseline emissions and qualify for a larger number of permits. The lesson: Appropriately restrictive—and verified—baselines are required; industry should not be allowed to manipulate the system.

The second major flaw was that CO_2 allowances were allocated for free to industry, but the structure of the electricity market allowed power producers to incorporate the market price of emissions allowances as a variable cost. In tight unregulated power markets, nuclear- and coal-power producers with low production costs and natural-gas-power producers with extra allowances were able to realize windfall profits as electricity prices increased to reflect the variable cost of carbon-emissions credits in the spot market. This effectively transferred income from consumers to the firms' shareholders: In 2006, it contributed to the doubling of electricity rates in the UK. The widely held view that giving allowances to producers for free would protect consumers was proven wrong. The lesson: How, to whom, and how many allowance grants are issued, as well as market structure, affect who wins and who loses as the market price of electricity fluctuates.[74]

[72] The EU excluded industries, such as airlines, that would become uncompetitive if saddled with a regulatory burden that rivals based in other jurisdictions did not face. This suggests that the ETS can only become more effective if other countries adopt carbon-emissions-reduction measures, which would make competitive concerns unnecessary.

[73] http://www.Americanprogress.org

[74] Some studies suggest that firms should receive only 15% of the value of allowances free to compensate for higher production costs. Lawrence Goulder, "Mitigating the Adverse Impacts of CO_2 Abatement Policies on Energy Intensive Industries," *Resources for the Future* (March 2002): Table 3

Also in 2006, some countries' allocation plans were leaked to the market by administrative error, and the carbon price collapsed in April when it became clear that there was an oversupply of credits. The clear lesson here is that transparent and fair disclosure of material information is necessary for smooth market operations.

More generally, the biggest flaw of the ETS was that it did not reduce carbon emissions enough: Despite compliance by regulated entities, the policy failed to achieve its goal. The caps were simply not low enough or applied widely enough. Other regulatory measures, such as efficiency standards, may also be required.

The EU, which plans to continue to regulate CO_2 indefinitely in parallel with future global regulatory agreements, will seek to remedy the ETS's shortcomings before 2012.

Carbon-Offset Projects

The Kyoto Protocol established carbon-offset projects as another way to reduce absolute emissions and encourage investment flows and technology transfer to developing countries. Such projects must be approved and verified by a division of the United Nations. The rules permit a regulated entity to take steps toward meeting its emissions-reduction requirements by investing directly in projects that reduce emissions in the developing world or by buying offsets from a project developer. Carbon-offset projects, termed Clean Development Mechanism (CDM) and Joint Implementation (JI) in the Kyoto Protocol, have been used by many Japanese and European firms to meet their emissions-reduction targets.

Major investment banks and trading houses have begun to build specialized project finance units to meet market demand for these services. Most of their early investments have been infrastructure projects that reduce emissions of greenhouse gases in China, India and Brazil. Typically, these projects are financially viable only because regulated entities in the developed world need to purchase emissions credits and the abatement costs on these particular opportunities are extremely low—as low as $5 per tonne, in many instances.

Many of the projects reduce emissions of greenhouse gases other than CO_2. One such gas is trifluoromethane (CHF_3), a refrigerant also used to coat plasma screens, which is nearly 12,000 times more potent than CO_2 and has an atmospheric life cycle of several hundred years. Because of the low cost of reducing CHF_3 emissions through substitution and their high value in CO_2-equivalent terms, such projects have been lucrative for early project developers.

Our research suggests that most of the richest opportunities are already being exploited. Emissions permits will have to become scarcer and more valuable for many more of these projects to be economically viable.

Whether carbon finance projects and trading will grow from a small market remains to be seen. The EU has limited the volume of permits from this source over the second compliance period, which will influence the permit price as volume reaches the allowed limit. Because they are seen as an important way to engage developing nations in emissions reduction, some version of the CDM may be part of a new global agreement beyond 2012.

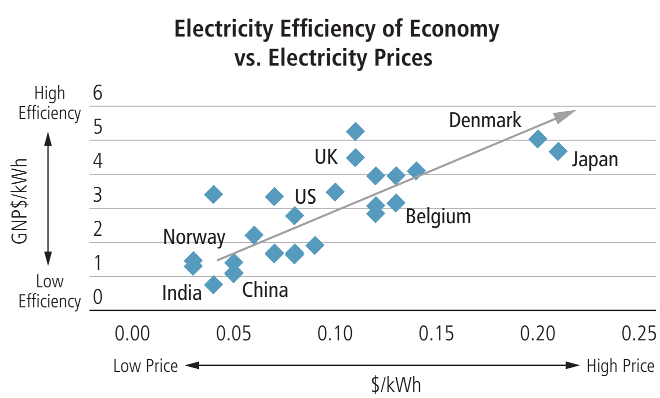
Energy-Efficiency Standards

Finally, carbon emissions can be cut by reducing the fossil fuels needed to accomplish a specific task by increasing energy-efficiency standards and electric-efficiency standards for consumer and industrial applications. For maximum impact, such efficiency standards would have to cover all major sources of CO_2 emissions: electric-power plants, industrial businesses, motor vehicles, buildings and appliances.

Energy-conservation efforts have been successful in Japan, Europe and California, where energy is expensive (because of taxes and reliance on imports) and where policymakers are focused on the issue. Raising prices is an effective way to reduce energy and electricity consumption relative to economic activity: In countries where electricity is relatively cheap because of subsidies (China and India) or because hydroelectric power is available (Norway), economic output per unit of electricity used is low (*Display 61*). In countries where

Display 61

Price of Electricity Tends to Drive Efficiency



Data from 2000
Source: EIA, World Bank and AllianceBernstein

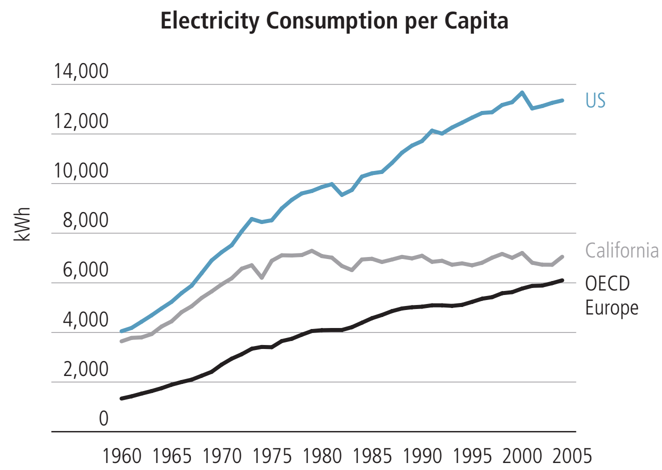
electricity is expensive, usually because of high taxation (as in Denmark), economic output per unit of electricity used is high. Thus, we expect efficiency improvements to be both the direct result of regulatory requirements and the indirect result of higher electricity prices.

Regulatory requirements are also effective at increasing energy efficiency: While electricity consumption per person has risen steadily in the US, electricity consumption per person has remained flat in California, which adopted stringent energy-efficiency standards two decades ago (*Display 62*). Clearly, regulation worked—and without damaging California's economy. This wealthy, populous and growing end market encouraged ingenuity in the development of more efficient products; the products have sometimes displaced less efficient options even in jurisdictions without stringent regulations. Tough regulations in the large California market have frequently led to product enhancements sold globally.

We discuss efficiency and technology forcing in more detail in the next section. ■

Display 62

Efficiency Gains Can Dramatically Cut Electricity Consumption



Source: California Energy Commission, California Public Utilities Commission, European Union and US Department of Energy

INCREASING ENERGY EFFICIENCY: THE LOWEST-COST ABATEMENT OPTION

Energy-efficiency enhancements are the low-hanging fruit—the lowest-cost and quickest way to reduce greenhouse-gas emissions—*if* the energy comes from fossil fuels. If the energy comes from nuclear-power or renewable-energy sources, energy-efficiency measures may reduce electricity and heating bills, but they will not help cut emissions. Because a very large part of total energy consumption today comes from fossil fuels, however, we expect higher energy and electricity prices and tougher efficiency standards in many countries to prompt or compel more efficient applications of many kinds. This would reduce fossil-fuel consumption and thereby reduce carbon emissions.

To understand how quickly and cost-effectively energy-efficiency enhancements can reduce CO_2 emissions, let's look at one example of what California was able to do in just 15 months during its painful electricity price squeeze of 2000–2001: The state government reduced its annual electricity consumption by 186 million kilowatt-hours, thus eliminating an estimated 74 kilotonnes of CO_2 emissions per year,[75] is simply by replacing all the incandescent bulbs in its outdoor traffic lights with brighter, more energy-efficient light-emitting diodes (LEDs).

This simple retrofit required an up-front expenditure of $50 million.[76] We estimate that eliminating the same amount of carbon emissions by developing and using a new carbon-free fuel source such as wind power would have cost twice as much up front, taken several years to implement and required paying $10–$15 million more in annual electricity bills. Thus, switching to the more efficient technology not only eliminated CO_2 emissions; it also saved time and money and reduced potential congestion on the electric grid.

What Energy Efficiency Is—and Is Not

Before going further, a few definitions are in order.

First, energy efficiency and electric efficiency are not synonymous, because not all energy is used in electrical applications: Buses, airplanes, some trains and most automobiles and trucks, as well as many heaters, furnaces and ovens, use energy primarily for mechanical, not electrical, applications. In this report, we discuss efficiency improvements in both mechanical and electrical applications if they can reduce fossil-fuel consumption and CO_2 emissions.

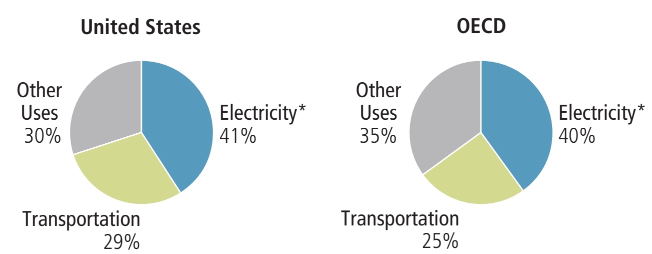
Second, energy efficiency is not synonymous with conservation. Conservation is the planned protection of a scarce resource or guarding against waste, without regard to how the resource is conserved. To many people, it implies sacrifice: loss of comfort or convenience, or making do with less. It may, for example, mean driving less; turning the thermostat down in winter (as US President Carter requested in 1979) or turning the air conditioner off in summer (as Japan's Prime Minister Koizumi asked in 2005). Energy efficiency, by contrast, means using less energy to produce the same amount of useful work. It is conservation without sacrifice.

Some regulatory efforts to reduce greenhouse-gas emissions may emphasize conservation that requires sacrifice. Our research, however, largely focused on the opportunities to reduce CO_2 emissions *without sacrifice* by reducing energy demand through efficiency improvements in motor systems and transportation. Together, these applications account for roughly 45% of total energy consumption in developed economies. Motors systems are a large source of electricity demand. Total electricity and transportation demand accounts for 65%–75% of energy consumption (*Display 63*). They are likely to constitute the bulk of the incremental energy demand from emerging economies, as well.

For both transportation and electricity, we concentrated on technological solutions that can enhance end-use efficiency—the amount of work that a motor, engine, air conditioner, computer or other application does relative to the energy input—because end-use efficiency is among the largest sources of potential energy savings

Display 63

Electricity and Transport Dominate Energy Demand



**Reflects energy used for power generation and heat plants in 2004*
Source: IEA

[75] About 57% of California's electricity use is from fossil fuels; in aggregate, every 1,000 kilowatt-hours of electricity consumed produces about 0.4 tonnes of CO_2-equivalent emissions. Data are from California Energy Commission, Audrey B. Chang, Arthur H. Rosenfeld and Patrick K. McAuliffe, "Energy Efficiency in California and the United States: Reducing Energy Costs and Greenhouse-Gas Emissions," 2007 and AllianceBernstein estimates.

[76] Includes cost of bulbs and installation. California Energy Commission and AllianceBernstein estimates.

across the energy value chain. Every unit of energy consumed by a consumer, business or other entity at the final demand stage typically requires 10–20 units of energy at the point of fuel extraction. For more detail, see "Types of Efficiency," on facing page.[77]

We expect the potential growth of certain technologies focused on energy-efficient improvements to be very significant over the near and medium term, creating several attractive investment opportunities.

The Past 30 Years

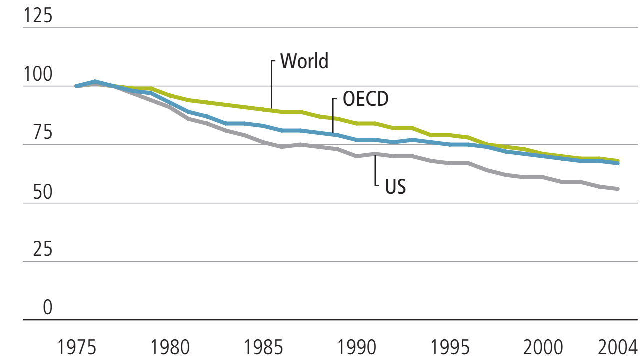
Improving energy efficiency has been a priority globally since mid-1973, when OPEC first withheld production to drive up oil prices. The efforts undertaken over the past 30 years have been remarkably successful: From 1975 to 2004, the world reduced its energy intensity—the amount of energy consumed per dollar of GDP—by about 32%, according to the World Bank. On average, developed economies achieved a 33% reduction (*Display 64*). The US achieved an even greater improvement: a 44% reduction in energy intensity.[78]

Some of the energy-intensity reduction in developed economies was a by-product of the shift from agriculture and manufacturing to services and of the relocation of some energy-intensive industries to the developing world. Nonetheless, a majority of the improvement appears to reflect the change in fuel mix from less efficient to more efficient sources, such as moving from oil to natural gas in home heating; from coal to natural gas and nuclear for power generation; and to more energy-efficient technologies and processes.[79] While it is difficult to quantify how much each of these factors contributed globally, a US government study concluded that one-third of the energy improvement in the US was due to structural changes in the economy, and the other two-thirds was due to greater energy efficiency, including changes in the fuel mix.[80] We think that these findings should be broadly representative.

Even if the shift in economic activity in developed countries continues to reduce energy intensity in these regions, the industrialization and greater prosperity in the developing world would probably drive aggregate

Display 64

Energy Intensity Has Improved Since First Oil Shock



Kilotonnes of oil equivalent per dollar of GDP, in constant dollars on a purchasing-power-parity basis
Source: World Bank

demand for energy higher. Furthermore, from a global emissions viewpoint, outsourcing energy-intensive industries is a zero-sum game. Therefore, reducing the energy intensity of the global economy will rest primarily on fuel-mix shifts and more efficient technologies.

The wide variation in energy efficiency among advanced economies shows that more can be done. Canada generates only US$3.40 of economic output (on a purchasing-power-parity basis) per kilogram of oil-equivalent energy consumed, while the US, with its larger service economy, has somewhat higher energy productivity, at $4.60 in output per kilogram of oil-equivalent energy consumed, according to the World Bank (*Display 66, page 64*). Western Europe and Japan are far more energy-efficient than either, with energy productivity scores of $6.50 and $6.40, respectively. Ireland takes the prize for energy efficiency among developed nations: It generates $9.50 in GDP per kilogram of oil-equivalent energy consumed. Ireland's lead in efficiency is largely due to a structural shift in Irish manufacturing over the past two decades toward less energy-intensive, but higher-value-added industries.[81] For the most part, the higher energy efficiency of Western Europe and Japan reflect higher prices of energy in countries with little or no domestic energy sources and policies aimed at encouraging efficiency.

[77] Amory Lovins, "More Profit with Less Carbon," *Scientific American* (September 2005); "Energy Efficiency, Taxonomic Overview," *Encyclopedia of Energy* (2004); Peter Huber and Mark Mills, *The Bottomless Well: The Twilight of Fuel, the Virtue of Waste, and Why We Will Never Run Out of Energy* (New York: Basic Books. 2005); and EIA

[78] Energy intensity, the amount of energy consumed per unit of GDP, is the inverse of energy efficiency, the GDP output per unit of energy consumed. Energy intensity is more frequently used for comparisons over time; energy efficiency is more frequently used for comparing different countries or applications.

[79] IEA, *Oil Crises and Climate Challenges: 30 Years of Energy Use in IEA Countries* (2005)

[80] US DOE, "National Energy Policy: Report of the National Energy Policy Development Group" (May 2001)

[81] "Energy Efficiency Profile: Ireland," from www.odyssee-indicators.org

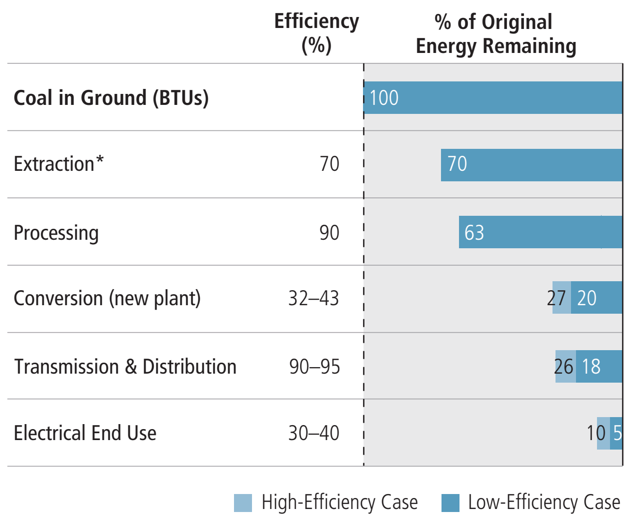
TYPES OF EFFICIENCY

Harnessing energy to do work involves a chain of processes, each with its own efficiency profile. The overall efficiency rate is the result of multiplying together the efficiency rates of each link in the chain for a fuel.[82] In this example, we use coal (*Display 65*).

- *Extraction efficiency* is the total amount of raw coal actually obtained by mining relative to a theoretical maximum. The average extraction efficiency for surface and deep mining coal is roughly 70%.
- *Processing/refining efficiency* is the usable energy of the coal after it has been processed and/or refined at a mine and transported to a power plant relative to the energy content of raw coal upon extraction. It is typically about 90%. Thus, complete efficiency for extracting, readying and delivering coal to power plants is about 63% (70% × 90%).[83]
- *Conversion efficiency* is the usable energy produced from the processed coal relative to the energy contained in the coal when delivered to a plant. The conversion efficiency of burning coal to produce electricity without carbon capture in a new facility is about 34%–43%, depending on the type of coal, steam temperature and pressure, and other factors.[84] The average conversion efficiency among the global fleet of coal plants in 2006 was about 32%, according to the IEA.
- *Distribution and/or transmission efficiency* is the energy delivered for use to a desired location relative to the amount of energy released for delivery. The transmission and distribution efficiency of delivering electricity from a generating plant to a home or building is typically 90%–95%, according to ABB.
- The *end-use efficiency* is the amount of work an application (such as an air conditioner, industrial motor or computer) produces relative to its energy input. Since many electrical applications operate on direct current (DC) and electricity is delivered as alternating current (AC), the end-use efficiency often includes the efficiency of converting AC to DC, which is typically 65% efficient, the Climate Savers Computing Initiative estimates. The overall end-use efficiency of home appliances such as dishwashers and toaster ovens is about 30%–40%.

Display 65

90% of Coal Energy Is Lost Before Getting to the End User



**Average of deep and surface mining*

Source: Amory Lovins, "Energy Efficiency, Taxonomic Overview"; Encyclopedia of Energy, 2004; *Huber and Mills,* The Bottomless Well *(see p. 62 n. 77); L. R. Radovic,* Energy and Fuels in Society, *(1992); and AllianceBernstein*

Since the overall efficiency rate is the result of multiplying the efficiency rates of the various steps, your air conditioner may only do work equal to 5%–10% of the energy in the raw coal in the ground that powers it:[85] 70% × 90% × (32%–43%) × (90%–95%) × (30%–40%)= 5%–10%. ■

[82] Amory Lovins, "More Profit with Less Carbon," *Scientific American* (see p. 62, n. 77); "Energy End-Use Efficiency," Rocky Mountain Institute (Sept. 19, 2005)

[83] L.R. Radovic, *Energy and Fuels in Society* (1992); Brent Sorenson, RUC Institute.

[84] John Deutch et al., "The Future of Coal," 2007

[85] See ABB's presentation at the Electric-Power Generation Conference, 2007; Amory Lovins, "Energy Efficiency, Taxonomic Overview," *Encyclopedia of Energy*, 2004; Huber and Mills, *The Bottomless Well*. These studies do not include the losses in the extraction and processing/refining fossil fuels used to generate electric power.

Display 66

Energy Efficiency Varies Widely by Country

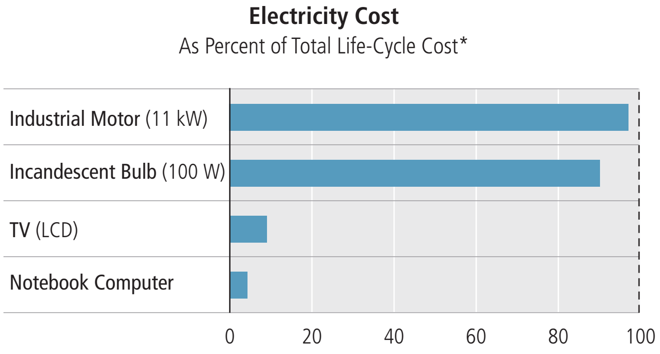
	2004		2004
Ireland	$9.50	Australia	$4.80
Switzerland	8.30	United States	4.60
Italy	8.20	Sweden	4.50
Denmark	7.90	Romania	4.50
Greece	7.40	Singapore	4.40
Argentina	7.40	China	4.40
Israel	7.30	South Korea	4.20
Austria	7.30	Malaysia	4.10
United Kingdom	7.30	Indonesia	4.10
Portugal	7.10	Czech Republic	4.00
Spain	6.90	Finland	3.80
Brazil	6.80	South Africa	3.70
Japan	6.40	Jordan	3.60
Turkey	6.20	Canada	3.40
Germany	6.20	Oman	3.00
Chile	6.10	Iceland	2.50
Hungary	5.90	United Arab Emirates	2.20
France	5.90	Kenya	2.10
Norway	5.90	Russian Federation	2.00
Netherlands	5.80	Saudi Arabia	2.00
Mexico	5.50	Ukraine	2.00
India	5.50	Kuwait	1.90
Belgium	5.20	Kazakhstan	1.90
Poland	5.10	Bahrain	1.80
New Zealand	5.10	Nigeria	1.40
Egypt	4.90	**World**	**4.70**

US dollars of GDP per kilogram of oil equivalent in constant dollars on a purchasing-power-parity basis
Source: World Bank

We estimate that by 2030, broad adoption of energy-efficient technologies in the nontransport sectors could reduce global electricity use by about 10%. This reduction will be mainly due to improved end-use efficiency of electric motor systems for industrial and residential applications. Since this product category is the single greatest user of electricity, and electricity costs tend to represent the overwhelming majority of the cost of ownership, as electricity prices rise users will look for ways to reduce their electric consumption.

Display 67

Electricity Is Much Higher Share of Total Cost for Motors



**Cost of equipment, electricity to operate and maintenance*
Source: American Council for an Energy-Efficient Economy; Baldor Electric; Conrad Brunner, "Standards for Energy Efficiency of Electrical Motor Systems"; and Saving Electricity (www.michaelbluejay.com)

The use of these energy-efficient systems will reduce demand even further in the distant future, but our model is confined to outcomes through 2030. The main limiting factor over our time horizon is conversion of the existing base of equipment. While we assume that efficient solutions will achieve significant penetration of sales well before 2030, replacing the existing stock will take decades.

The most substantial conversions we have modeled are for electric motors and drives: We expect efficient solutions to account for about 30% of the motor stock by 2030. We expect the highest conversions in this product category in part because, as the single greatest user of electricity, it is likely to be the most strictly regulated. In addition, electricity costs represent the overwhelming majority of the cost of motors over their full lives (*Display 67*). So as electricity prices rise, users will look for ways to reduce their electric consumption. In all other cases, we expect conversion of about 20% of the relevant stock since the remaining applications each account for a smaller share of total electricity use and hence consumers' electric bills, delaying their likely adoption. Further, certain applications such as LEDs require special lighting fixtures, which could delay conversion to advanced lighting.

We estimate that the 10% reduction in demand for electricity because of greater end-use efficiency in nontransport sectors would eliminate 2%–4% of total projected emissions in 2030. Both the absolute and percentage reduction in emissions would depend on how clean power generation becomes. In our business-as-usual case, a 10% reduction in electricity demand due to more efficient applications would cut overall CO_2 emissions by 1.6 gigatonnes, or approximately 4%, in 2030. Under our abatement scenario, power generation becomes much cleaner, so use of efficient applications reduces emissions by only about 0.6 gigatonnes, about 2%.

Within the transport sector, improved energy efficiency would also have an impact, most of it from strong market penetration of hybrid electric vehicles, which we discuss later in this report.

Electricity Demand Trends

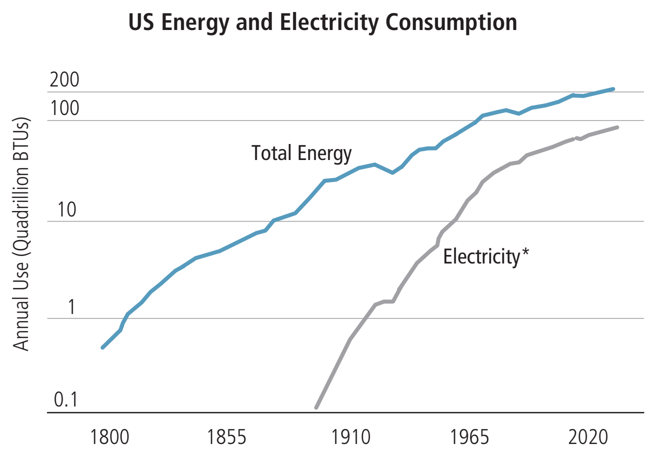
Global demand for electricity has grown 3.6% a year on average since 1971, more than double the 1.7% demand growth for all energy uses combined. Indeed, electricity has been one of the fastest-growing uses of energy[86] (*Display 68*). This trend is widely expected to continue because electricity use tends to rise with economic development and prosperity: Economic development requires electricity to expand the production of goods and services and improve productivity, which increases prosperity, which in turn leads to more widespread consumer access to the electric grid and more widespread use of refrigerators, washing machines, air conditioners, televisions and so on. Rapid growth in communications and information technology has also increased demand for electricity.

Another, less well-recognized, driver of increased electricity demand is the switch in many industries from mechanical systems, including engines, gears, pulleys, belts, drives and transmissions, to electrical systems, including motors and actuators, automation and robotics. An analysis of the US by Peter Huber and Mark Mills suggests that nearly 70% of GDP in advanced economies is powered by electricity, versus mechanical engines and boilers[87] (*Display 69*). We expect electricity to account for an even larger share of GDP as thermal processes in industry are converted from conventional heating sources to electrically powered microwaves and lasers, and as the transportation sector migrates to electric power.

Like energy use more broadly, electricity usage around the world has become more efficient: Despite the dramatic switch from mechanical to electrical processes, electricity used per unit of GDP output fell at a compound annual rate of 0.5% from 1992 to 2004.[88] Electric-efficiency gains have varied widely by country, largely in line with the price of electricity, as we showed in Display 61 on page 59.

Display 68

Electricity Represents a Growing Share of Energy Demand

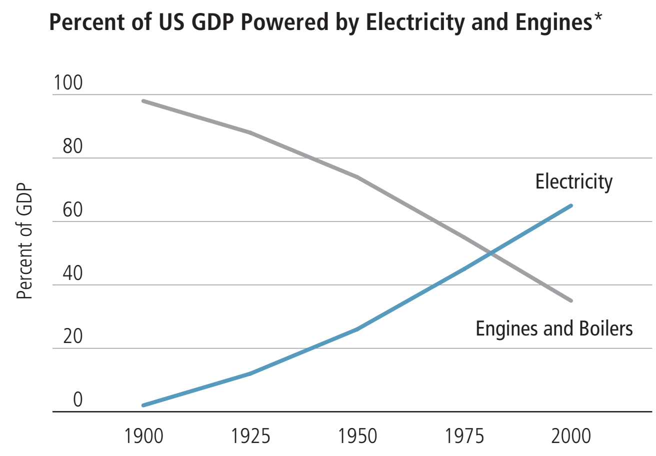


**Energy consumed to produce electricity*

Source: EIA Annual Energy Review *2003; Huber and Mills,* The Bottomless Well*; and US Census Bureau Historical Statistics of the United States, Colonial Times to 1970*

Display 69

The Switch to Electrical Systems Is Well Under Way



**Excludes residential uses*

Source: EIA; Huber and Mills, The Bottomless Well*; and US Census Bureau*

86 EIA, IEA and World Bank

87 Huber and Mills, *The Bottomless Well*

88 World Bank and AllianceBernstein estimates

HOW CALIFORNIA DID IT

California's leadership in energy efficiency is largely due to the efforts of Arthur Rosenfeld, once a particle physicist in charge of a Nobel Prize–winning research team at the Lawrence Berkeley National Laboratory (LBNL). When the first OPEC oil embargo began in 1973, Rosenfeld calculated that if the US had been using energy as efficiently as European nations or Japan, it could have *exported* oil instead of rationing it when the embargo cut supplies. Soon after, Rosenfeld changed his career to pursue energy efficiency: He created the Center for Building Science at LBNL.

The tools, technologies and policies the center devised have had a tremendous impact. To reduce energy use for heating and air conditioning, the center developed insulated windows, reflective roofs that do not absorb heat and wall insulation. It also paved the way for the invention of the compact fluorescent lightbulb and for efficient air conditioners, furnaces, water heaters and refrigerators. The center also helped establish California's tough appliance and building standards, which have been emulated by many states, the US federal government and other countries around the world.

Efficiency Standards

To start, Dr. Rosenfeld and his staff studied refrigerators. They found that many were "energy hogs" with uninsulated doors, thin walls, inefficient motors and poor heat exchangers. Furthermore, they found, stores did not readily disclose efficiency rates, nor did they price models based on energy consumption. Consequently, consumers had almost no way to make informed purchases. Center staffers told then-governor Jerry Brown that if the state allowed only the most efficient refrigerators to be sold, it could reduce annual consumption of electricity in the state by an amount equal to the annual power generated by a nuclear plant. Governor Brown wanted to stem the construction of new nuclear plants, which the utility industry was claiming were necessary to meet future demand growth, so he agreed to adopt the policy.

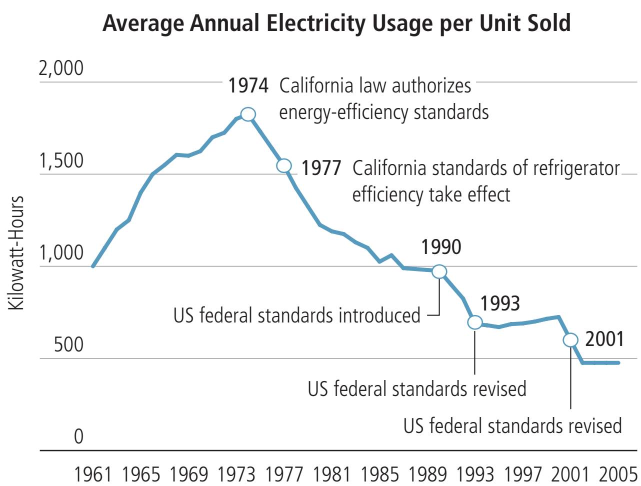
In 1974, California became the first jurisdiction to introduce appliance standards, employing what is known as a technology-forcing strategy to drive innovation. Since this populous and wealthy state was (and is) an enticing market, many manufacturers designed products to meet California's requirements. Frequently, the manufacturers offered the same products elsewhere, as well, even before other states adopted similar standards and US federal standards were introduced in 1988.

California continues to be at the forefront of energy efficiency by periodically modifying, strengthening and expanding its appliance standards. As a result of California's leadership, average annual electricity consumption for new refrigerators sold in the US has declined by 71% in aggregate from 1974 to 2002, although the size of the typical new unit has increased by 29% (*Display 70*).

Dr. Rosenfeld also formed a group at LBNL to create a computer program to help design buildings so that they would need minimal air conditioning in summer and minimal heat in winter. This program became the basis for setting energy-performance standards for buildings in California (known as Title 24) in 1978. Several other states, the US federal government and other countries followed soon thereafter.

Display 70

Regulation Drove Huge Gains in Refrigerator Efficiency



Source: American Council for an Energy-Efficient Economy (ACEEE), International Rectifier, US Department of Energy and AllianceBernstein

In 2004, California's Air Resources Board adopted the most stringent fuel-economy standards for automobiles in the world. These standards, later enshrined in state law, stipulated that CO_2 emissions from vehicles had to be reduced by 30% by 2016. The law is now being contested in court by the auto industry and the US government.

Decoupling Utility Revenues and Profits

In 1982, California embarked on another first. At the urging of Dr. Rosenfeld and other energy experts, it adopted an innovative approach to utility regulation, called decoupling, which broke the link between utilities' profits and electricity sales. Instead of rewarding utilities for increased revenues, decoupling rewards them for meeting customers' electricity-service needs. Decoupling gives utilities the incentive to make least-cost investments for the delivery of reliable electricity service to customers even if the investments reduce sales. It removes both the incentive to increase sales of electricity and the disincentive to implement effective efficiency programs.

Studies have found that decoupling is much more effective at providing reliable service and increasing efficiency than frequent rate changes or lost-revenue adjustments.[89] Because it lowers the amount of electricity sold, it reduces fuel intake and burning by power plants. If the power plants burn fossil fuels, carbon emissions are also reduced.

In a decoupled regulatory structure, state regulators determine every few years how much revenue utilities need to cover certain approved costs. Electricity rates are set at the level that allows utilities to recover these costs, based on a sales forecast. If actual sales are above this forecast, excess collections are given back to consumers in the form of reduced rates. If they are lower, rates are raised modestly.

Utilities in California responded favorably to the policy because it helped stabilize their finances. Since then, regulators in Idaho, Maine, Minnesota, New York, Oregon and Washington have adopted or have begun to consider decoupling mechanisms of their own. Italy, the UK and France also appear to be evaluating decoupling relative to other policies aimed at promoting energy savings.

Loading Order

After Dr. Rosenfeld was appointed to the California Energy Commission in 2000, the commission established a "loading order" of preferred energy resources. The loading order is a three-rung hierarchy for meeting future energy needs.

Top priority is given to electric efficiency and demand-response mechanisms (such as advanced metering and dynamic pricing). Utilities are required to invest in electric efficiency whenever it is cheaper than procuring power[90] and to adopt an administrative structure that integrates electric efficiency into utility procurement. Utilities are also required to adopt demand-response mechanisms that encourage consumers to reduce demand at peak hours. Since electrical systems are generally built to meet peak demand, lowering peak demand reduces overall capacity and capital requirements.

The next priority is investing in renewable-energy sources. By 2010, the state aims to have 20% of its electricity come from renewable sources such as geothermal, wind and solar. This is having ripple effects on neighboring states, because California buys more electricity than it produces and applies its carbon-emissions restrictions to imported power. This priority underscores the political impetus for renewable-energy sources, regardless of their cost-effectiveness.

Lastly, when utilities cannot meet anticipated power needs through electric efficiency, demand-response and renewable solutions, they must invest in cleaner and more efficient fossil-fuel generation. ■

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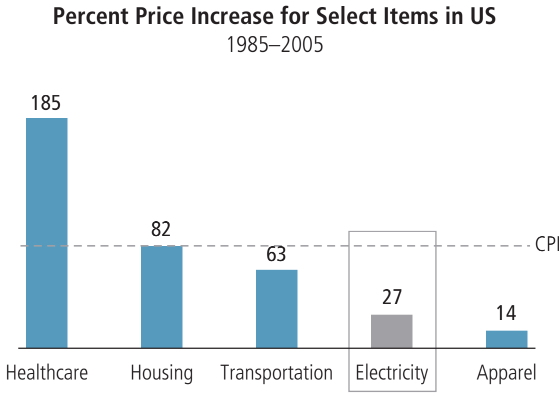
[89] Sheryl Carter, "Breaking the Consumption Habit: Ratemaking for Efficient Resource Decisions," *The Electricity Journal*, 14, n. 10 (Natural Resources Defense Council: December 2001): 66–74; Joseph Eto, Steven Stoft and Timothy Belden, "The Theory and Practice of Decoupling Utility Revenues from Sales," *Utilities Policy*, 6, n. 1 (LBNL: March 1997): 43–55.

[90] According to the California Energy Commission, California Public Utilities Commission and the Natural Resources Defense Council, the average cost of electric-efficiency programs is about half the cost of base-load generation; these programs have been found to save electricity at a cost of three cents per kilowatt-hour, less than half the cost of building new generating plants.

Display 71

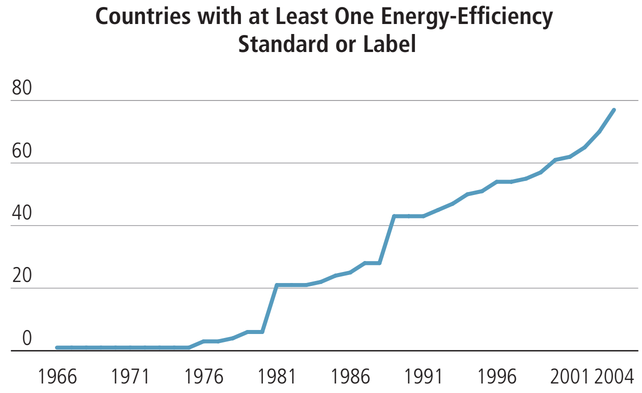
Electricity Prices Have Remained Relatively Low



Data are not adjusted for inflation.
Source: Edison Electric Institute

Display 72

Efficiency Standards Have Become Pervasive



Source: Collaborative Labeling and Appliance Standards Program and IEA

The US has about average electrical efficiency, because it has about average electrical prices. Electricity prices in the US have risen much more slowly than the Consumer Price Index since 1985 (*Display 71*). That is, the real price of electricity has declined! As a result, businesses and consumers have been relatively slow to seek greater efficiency. As California Energy Commissioner Arthur Rosenfeld observed, "What's dirt cheap tends to gets treated like dirt."[91]

California, however, has actively promoted greater end-use efficiency through stringent standards for appliances and building (determined and enforced by local and state authorities) and energy-efficiency programs (administered by utilities). Over the past 30 years, these efforts have reduced the state's electricity demand by over 40,000 gigawatt-hours a year (or 15% of California's annual electricity use in 2003), avoided construction of 12 gigawatts of new capacity, and reduced carbon emissions from its power sector by nearly 20% compared with estimates of what would have happened without the standards and programs.[92] (See "How California Did It," page 66.)

According to the IEA and the Collaborative Labeling and Appliance Standards Program (CLASP), 77 countries representing more than 80% of the world's population and 90% of global GDP now have efficiency standards and/or labeling for some electric devices, such as home appliances and electronics, lighting and office equipment (*Display 72*).

The EU has proposed requiring an additional 20% improvement in the efficiency of home appliances and plans to develop industrial motor standards in 2008. The US Department of Energy is also evaluating new standards for industrial motors and drives, which are expected by 2009. Stricter efficiency standards for a wide range of other products are also under consideration in the US.

China, India, Mexico, South Africa and South Korea, along with a host of other developing countries, are also moving toward minimum energy-performance standards for a range of appliances, equipment and lighting. Australia and New Zealand recently issued new standards as well.[93] There is also considerable effort being undertaken by regulators in many countries to harmonize energy-efficiency-testing procedures, efficiency classes and labeling policies, and to introduce worldwide standards for electric motor systems acceptable to most countries by the end of 2008. The standards, initially, would be voluntary, but they may become mandatory after two years.[94]

Such efforts are only the beginning, we believe, of a large-scale effort to increase efficiency that will help reduce carbon emissions and create significant investment opportunities in new technologies. ■

[91] Steven Mufson, "In Energy Conservation, California Sees Light," *Washington Post* (February 17, 2007)

[92] Chang et al., "Energy Efficiency in California and the United States: Reducing Energy Costs and Greenhouse-Gas Emission," (see p. 61 n. 75)

[93] IEA and Collaborative Labeling and Appliance Standards Program

[94] Standards for Energy Efficiency of Electrical Motor Systems, www.seeem.org

ENHANCING THE EFFICIENCY OF ELECTRIC APPLICATIONS

Our research shows that the greatest opportunities to increase the end-use efficiency of electricity lie in improving the efficiency of electrical motor systems. Lighting, electronic devices, data centers, high-voltage direct-current transmission lines and superconductors also offer potential. Here, we review each of these developments and the investment opportunities they create.

Electrical Motor Systems

An electrical motor system is technically defined as a combination of electrically driven equipment that converts electrical energy to mechanical or fluid power.[95] The core elements are a motor unit and controller. The controller, also referred to as the drive, is a device or group of devices that serves to govern the performance of the electric motor. It may include a mechanical or electrical process for starting and stopping the motor, selecting forward or reverse rotation, selecting and regulating the speed, regulating or limiting torque, and protecting against overloads and faults.

Motor systems run industrial equipment, home appliances and the heating, ventilation and air-conditioning systems for buildings. In the US, Western Europe, Japan, South Korea and China, motor systems account for 50%–60% of all electric consumption.[96]

A particularly large reduction in electricity consumption and carbon emissions can be gained by improving the end-use efficiency of the large (at least one horsepower) motor systems typically found in industrial and commercial applications. All else being equal, motors with more horsepower (hp) consume more electricity in any given period of operation. Industrial motors also typically operate for many hours a day. A survey by the US DOE found that motors of 50 or more horsepower account for less than 5% of all motors used in the industrial sector, but over 70% of the full group's electricity consumption.[97]

Improving the efficiency of the smaller, but not tiny, motors in the residential sector that run for relatively long periods, such as refrigerators and heating, ventilation and air-conditioning (HVAC) systems, can also have a sizable impact because they are so numerous.

Display 73

Energy-Efficient Motor Systems Offer Dramatic Savings, Fast

	Base Motor System	Variable-Speed Motor System
Motor Size (hp)	100	100
Average Power Output* (hp)	60	60
Price of Electricity† ($/kWh)	0.06	0.06
Motor System Efficiency	60%	80%
Motor System Cost ($1,000s)	5.0	10.2
Annual Electricity Cost ($1,000s)	**39.2**	29.4
Payback Period	**—**	**6 Months**

Kilowatt-hours used by a motor in a year =

$$\frac{\text{Average Power Output}}{\text{Motor System Efficiency}} \times \frac{\text{8,760 Hours}}{\text{1 year}} \times \frac{\text{0.746 kilowatts}}{\text{1 horsepower}}$$

**Average power output varies with frequency of use and load factor.*

†Average retail price for US industrial users of electricity in 2006 was $0.06.

Source: EIA and AllianceBernstein

The efficiency gains from advanced motors and drives can be implemented at relatively low cost, so the payback through lower monthly electricity bills can be rapid (*Display 73*). The cost of a motor system varies from a hundred dollars to several thousand dollars, with motor output largely determining its cost. Depending on the frequency of use and the price of electricity, we estimate that the payback period can be as short as several months or as long as several years. Individuals who do one load of laundry a week will take far longer to recoup the higher up-front cost of an energy-efficient washer than a family that does laundry daily. If the family lives in an area with high electricity prices (such as Japan or California), it will recoup the up-front cost faster than if it lives in an area with low electricity prices, such as Norway. Motor size relative to the typical load requirement also affects the payback calculation. If the motor almost always operates with full (or maximum) load, there is less opportunity to improve system efficiency.

95 For more information on motor systems, see US DOE, Office of Industrial Technologies Motor Challenge Program; and the Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory (LBNL).

96 American Council for an Energy Efficient Economy (ACEEE); Beijing Energy Efficiency Center; EPRI; European Commission; IEA; International Rectifier; Jolient Technologies; KEMCO; LBNL; Standards for Energy Efficiency of Electric Motors (SEEEM); US DOE; Bimal Bose, "Power Electronics and Motor Drives—Recent Technology Advances," IEEE (2002); Howard W. Penrose, "Motor Facts—Motor Circuit Analysis," *Electrical, Construction & Maintenance Magazine* (March 1, 2003); and Samuel F. Baldwin, "The Materials Revolution and Energy Efficient Electric Motor Drive Systems," *Annual Review of Energy*, vol. 13 (Center for Energy and Environmental Studies, Princeton University, November 1988).

97 David Mueller, "Cooling Off Energy Use," *Environmental Protection* (2001); US DOE, *Energy-Efficient Electrical Motor Selection Handbook* (1993)

The Problem with Traditional Motor Systems

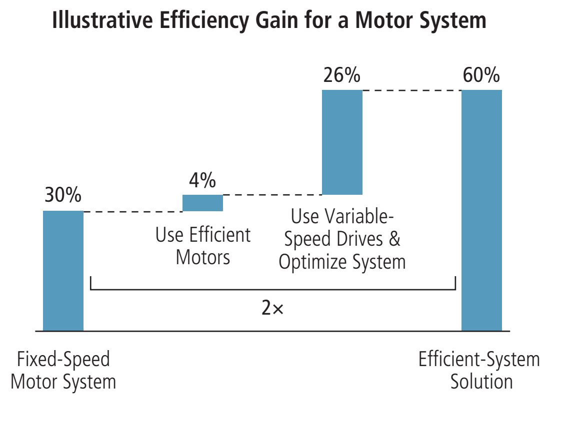
Most motors already have internal efficiency ratings of 75% or higher,[98] so using a more efficient motor only improves the efficiency of the system by 3%–5%. The inefficiencies in traditional motor systems typically come from a mismatch between the motor's speed and the system's load. Variable-speed drives and optimization can increase efficiency enormously, mainly by better aligning motor speed with system load[99] (*Display 74*).

Most traditional motors operate at a constant speed; typically, the motor size for an application is chosen to handle the maximum load requirement. When a given load requires less than maximum power, the motor still operates at its uniform speed, delivering full power. Thus, it wastes energy. A comprehensive study by the US DOE found that about 40% of industrial motors routinely operate at 40% of full load or less.[100] To match the output of the motor with the power required at a given time, the energy flow from the system is often mechanically restricted by a throttle (in the case of a pump) or a damper or vane (in the case of a fan). These controls reduce energy consumption somewhat, but they are not very efficient.

Imagine a car with an engine that only runs at one speed, never changing gears, and that the only way to slow it down is to brake while still pressing the gas pedal. While braking would indeed slow the car, it would require much more energy than a normal car that, manually or automatically, changes gears and can ease up on the gas pedal. A conventional pump system works much like our imaginary one-speed car engine (*Display 75*): The motor operates at a constant speed, but when necessary, a throttle on the pipe chokes off flow. While the pressure that builds up in the constricted pipe reduces the power required, it does so inefficiently. A much greater reduction in power consumption could be achieved by slowing the motor speed to reduce the flow into the pump (*Display 76*).

Display 74

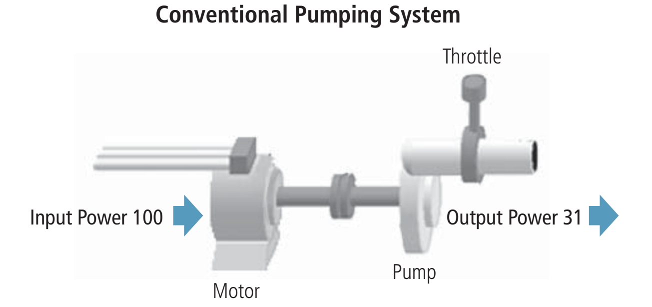
A Road Map to Improved Efficiency



Source: European Committee of Manufacturers of Electrical Machines and Power Electronics (CEMEP), Frost & Sullivan, IEEE, Motor Challenge Program of the European Commission, Nadel et al. (ACEEE) and US DOE

Display 75

Mechanical Throttles Waste a Lot of Energy



Source: Energy Efficient Motor Driven Systems, European Copper Institute and Motor Challenge Program of the European Commission

How Variable-Speed Drives Work

Variable-speed drives do exactly that: They adjust motor speed to load requirements, where possible, thereby avoiding delivery of more power than required to perform the task at hand. Also called adjustable-speed drives and variable-frequency drives, variable-speed drives seek to align motor speed with load through frequency control. They have four major components: rectifiers, inverters, filters and microcontrollers/sensors.

The *rectifiers* convert alternating current (AC) from the electrical grid to direct current (DC). Most often, they use transistors with gate circuits that can be opened and closed instantly by microprocessors to control the flow of power. Transformers may also be required if the incoming AC power supply is very high voltage. After the power is rectified, the *filter* or DC bus smoothes the power.

The *inverter* precisely controls the power delivered to the motor and adjusts the motor speed. It contains robust power semiconductors—typically insulated gate bipolar transistors (IGBTs)—that electronically switch on and off the DC power several thousand times per

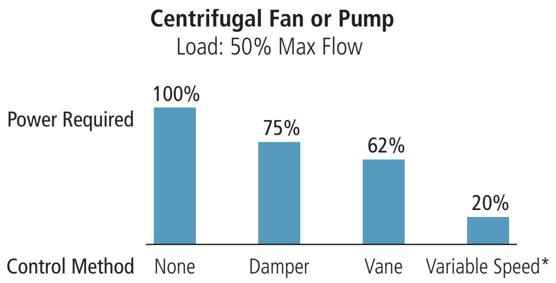
[98] Baldor Electric, European Commission, IEA and US DOE

[99] ABB, Baldor, CEMEP (Comité Européen de Constructeurs de Machines Electriques et d'Electronique de Puissance [European Committee of Manufacturers of Electrical Machines and Power Electronics]), European Commission, Infineon, IEA, IEEE, SEEEM and US DOE

[100] US DOE, *US Industrial Electric Motor Systems Market Opportunities Assessment* (1998)

Display 76

Variable-Speed Drives Can Be Far More Efficient



Figures derived from case studies

* *Theoretical minimum power required would be 12.5%.*

Source: Progress Energy, Variable-Speed Drives

second. Most inverters use a pulse-width modulation to produce a voltage waveform at a desired frequency.

The *microcontrollers* and *sensors* monitor load conditions and variations in source voltages, control power flow and specify the desired waveforms of power to be delivered to the motor to determine motor speed. They thereby align power consumption with varying load requirements.

In electronics applications, power consumption equals motor torque (the force required to turn a motor) times speed. The energy savings achieved by using a variable-speed drive depend on the application and load and can vary widely—from less than 10% to 80%.[101]

In *variable-torque applications*, such as centrifugal pumps, fans, blowers and compressors, torque is proportional to speed squared, so adjusting the speed can dramatically cut power required. Since power equals torque times speed, and torque equals speed squared, power equals speed cubed. If speed is reduced by 20%, the new power required will be $80\%^3$, or 51%. That is, power required would be reduced by 49%. Thus, in variable-torque applications, a mere 20% reduction in speed can lead to a 49% reduction in required power.[102] Variable-torque applications typically provide the greatest energy savings, ranging from 30% to 80%.

In *constant-power applications*, such as machine tools, torque is inversely related to speed: If speed falls by 20%, torque would increase by 20%, and power would remain unchanged. Thus, the energy savings from changing speed are minimal, and a variable-speed drive tends to provide little or no energy savings in machine tools.

In *constant-torque applications*, such as conveyors, elevators and escalators, torque is independent of speed. Because power equals speed times torque, a 20% reduction in motor speed for a variable-speed conveyor belt could result in a 20% reduction in power consumption, if the speed of the conveyor can be altered. Thus, constant-torque applications would get more benefit from a variable-speed drive than a constant power application, but less than a variable-torque application.

Regardless of whether the speed or load of the application can be changed, motor systems with variable-speed drives can achieve other energy savings, in four ways:

- They allow you to efficiently stop the motor for, say, an escalator or an elevator, when there is no one on it.
- They allow you to start and stop the motor softly. Starting a standard fixed-speed motor typically requires a surge of current nearly six times normal, versus the 1.5 times surge for a motor with a variable-speed drive. The sixfold surge usually results in 50% more power consumption, according to the Efficiency Office of Hong Kong. State-of-the-art escalators start gradually when someone walks in front of them; they move at the required speed by the time the person hits the first step.
- They eliminate mechanical controls, such as belts and gears.
- They can capture and reuse the energy now wasted in braking.

Thus, the Energy Efficiency Office of Hong Kong found that energy reductions of up to 60% can be achieved by escalators with variable-speed drives. A report prepared for the European Commission found that energy reductions of 65% or more are possible for elevators with variable-speed drives; if regenerative braking is deployed, the reductions can rise to 80% or more.[103]

Other advantages of variable-speed drives include reduced wear and tear on motors, which enhances their useful lives and lowers maintenance costs. They are also quieter and often enable various process improvements in industrial applications. For example, a variable-speed drive in a conveyor belt can allow the plant to run the belt more slowly on days when it is performing slow-paced tasks and faster when it is performing fast-paced tasks. Thus, the same assembly line can easily be adapted for different products and work processes.

101 ABB, American Council for an Energy-Efficient Economy, Baldor, CEMEP, European Commission, Government of Hong Kong, Infineon, IEA, Siemens and US Department of Energy

102 The 49% reduction in power required comes under ideal conditions. Usually, friction lessens this benefit to some extent.

103 Anibal de Almeida et al., report prepared for the Directorate General of Energy, European Commission (May 2001)

ABB estimates that worldwide, the majority of all motor systems in use are for variable-torque applications—those with the greatest energy-savings potential. Less than 5% are constant power applications, which provide the least energy-savings potential.

Sizing the Opportunity in Efficient Motor Systems

We expect the industrial sector to adopt variable-speed drives fairly quickly because it relies most on motors and uses many centrifugal motors, which are variable-torque and therefore can get very large efficiency gains through speed control (*Display 77*). The commercial sector stands to benefit primarily by using these drives in heating, ventilation and air-conditioning systems. The residential sector will benefit from their use in home appliances. Energy-efficient washing machines, which are available today, automatically determine the amount of water, heat and spinning speed required for each load, depending on the amount and type of fabric. They also eliminate mechanical belts and gears. The result is a 60% energy-efficiency gain over standard washers of similar size, if you include the energy savings from heating less water.

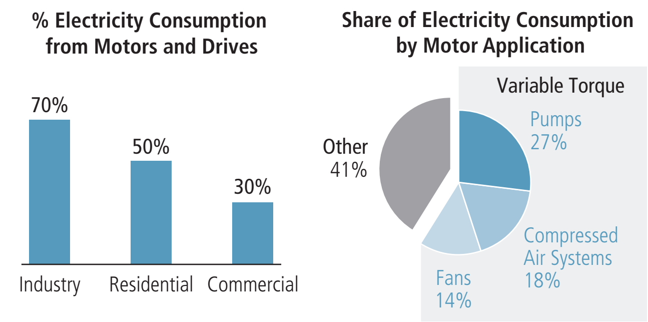
We estimate that globally, the electric-motor market (a subset of the electric-motor-systems market) had about $30 billion in revenues in 2005, with at least hundreds of millions of motors sold each year.[104] Efficient motors accounted for only $5 billion of the total. Frost & Sullivan, our proxy for the market consensus, expects the overall motor market to continue to grow at about 4% per year. We expect the market for efficient motors to grow at a compound rate of at least 15% as higher electricity prices and regulation motivate or compel accelerated adoption. Efficient motors will cannibalize sales of less sophisticated motors.

Our strong growth forecast for efficient motors reflects, in part, recent industry experience: Baldor Electric, a pure-play maker of electrical motors for industrial applications, has reported that its efficient motors business grew at a 30% annual rate over the past few years; the company expects the trend to continue. ABB, Amotech, Johnson Controls, Regal Beloit, Siemens and Teco Electric have also reported double-digit revenue growth for energy-efficient products, including motors, over the past three years.

Variable-speed drives are typically the highest-cost component of an efficient motor system after the motor; they are also the largest incremental cost of an efficient

Display 77

Industrial Sector Has Most to Gain from Variable-Speed Motors



Source: US DOE, "US Industrial Motor-Driven Systems Market Assessment"

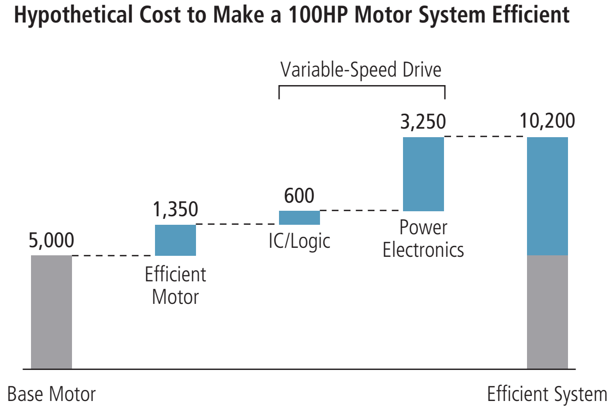
motor system (*Display 78*). According to Frost & Sullivan, the overall market for variable-speed drives was about $7 billion in 2005, with expected future annual growth of about 7%. Our forecasts are more aggressive: Since efficient motor systems need variable-speed drives, we expect sales of variable-speed drives to grow at a similar rate as efficient motors, or at least 15% a year. The rapid growth experienced by makers of advanced semiconductors for this market, including Infineon, International Rectifier, IXYS and Texas Instruments, also informs our forecast.

We can disaggregate the $7 billion overall market for variable-speed drives into two major categories of semiconductor components: integrated circuits/logic (such as sensors and microcontrollers); and power electronics (such as rectifiers and inverters). We estimate that in 2005, the power electronics subset had about $5.6 billion in sales and the logic subset had about $1.4 billion. For some companies, power electronics for variable-speed drives is likely to provide strong growth. In 2005, sales related to variable-speed drives represented about 25% of revenues for many firms that participate in this market segment. Because the overall market for logic semiconductors is much larger, however, sales related to variable-speed drives accounted for less than 2% of total global revenues. Thus, participants in the logic segment will not benefit as much from growth in variable-speed drives. Nonetheless, even if we assume steep average unit price compression (25% for integrated circuits/logic and 50% for power electronics over the next 10 years), the increase in penetration of efficient motor systems will likely represent an important growth opportunity for many semiconductor companies.

104 It is difficult to obtain precise data on global unit sales of electric motors and the current population of motors. Depending on whether fractional horsepower motors are included, estimated global unit sales range from hundreds of millions to 6 billion a year. The market data for motors cited in this report are from Frost & Sullivan, unless otherwise indicated.

Display 78

Variable-Speed Drives Are the Major Added Cost



Does not include cost reduction from elimination of mechanical parts
Source: driveswarehouse.com and AllianceBernstein

Energy-Efficient Lighting

Lighting presents another significant opportunity to improve the end-use efficiency of electricity. The incandescent lightbulb is over 100 years old. While its efficiency has improved since Thomas Edison's prototype (which was 1% efficient), it is still low at 2%–5%. Traditional fluorescent bulbs, which were introduced commercially in 1938, are 7%–15% efficient and last at least 10 times longer, but tend to have poor light quality and require special fixtures to accommodate their very long tubes. Compact fluorescent lightbulbs, introduced in the 1980s, combine the best of both: They are 7%–9% efficient, last nine to 10 times longer than incandescent bulbs, and produce equivalent brightness and a better quality of light than incandescent bulbs. They also fit into a standard light socket, although decorative lights and dimmers are still difficult to use with them.

Initially quite expensive, at $25 a piece, compact fluorescent bulbs now cost $6 on average. In most cases, this reduces the payback via energy savings for their up-front price premium versus incandescent bulbs to less than two years. Some policymakers are becoming concerned, however, that the mercury content of compact fluorescent bulbs makes safe disposal difficult.

The lighting market generates over $100 billion in sales per year. About 80% of the total is for fixtures and 20% for bulbs. Philips, GE and Siemens dominate the compact fluorescent bulb market, which is estimated at $2 billion. They are also the largest providers of incandescent lightbulbs, a $10 billion market. In the near term, these companies will likely experience growth in their lighting business as the more expensive compact fluorescent bulbs gain share from incandescent bulbs. But after compact fluorescents become the standard, their long lives will slow sales growth materially. Furthermore, the incandescent business has offered attractive returns, with estimated costs of about $0.03 per bulb versus a selling price to distributors of about $0.30 per bulb.[105] The returns on compact fluorescents are likely to be lower, at least in the near term.

Regulatory policy may spur additional action on the lighting front: Australia has banned use of the incandescent bulb after 2011. In Canada, Ontario may follow suit. In the US, California may. Wal-Mart's goal of selling 100 million compact fluorescent lightbulbs by 2008 is also likely to spur this transition.

The light-emitting diodes (LEDs) used to such good effect for outdoor lighting by the state of California, as well as fiber-optic and high-intensity discharge (HID) technologies, are also highly efficient, long-lived and potentially high-quality lighting alternatives. While they may become viable for mainstream indoor use in time, today they are best suited for outdoor lighting and other specialty uses because of their relatively high cost and difficult installation. Thus, they represent a smaller investment opportunity over the short term. Philips's recent $795 million acquisition of Color Kinetics, a Boston-based maker of LEDs, on the back of several other acquisitions along the LED value chain, suggests that the company believes that this technology is here to stay. Other established players may ultimately seek to participate in its growth as well.

Electronic Devices

Electronic devices such as computers and television sets collectively account for about 10%–15% of total electricity use in the US and a similar percentage in other developed countries. There are three principal technologies that could enhance their electrical efficiency: advanced power supplies, voltage regulators and power-management software. They are all being deployed to some degree.

One initiative on this front can be found in the US computer industry: the Climate Savers Computing Initiative (CSCI). Led by Google and Intel and backed by Advanced Micro Devices, Dell, Hewlett-Packard, Microsoft and Sun Microsystems, the CSCI has committed

105 Jonathan Dorsheimer, Canaccord Adams lighting analyst

to produce systems and components that meet power-efficiency targets far more stringent than existing US regulatory guidelines. For instance, most power supplies used today convert AC power from the grid to usable DC power with a device that operates at about 65% efficiency. Energy Star, a federal voluntary program in the US, has a target of 80% efficiency; CSCI has a target of 90% efficiency by 2010. CSCI also aims to raise the efficiency of voltage regulators (described below) from 80% to 95%. It has not established explicit targets for the global power-electronics market as a whole.

CSCI also plans to push manufacturers to install robust power-management software in computers so that they automatically switch into low-energy, standby mode when inactive. The IEA and Power Integrations estimate that 5%–15% of household electricity consumption worldwide is wasted in standby mode. There have been voluntary initiatives to reduce the standby power consumption of most electrical products to one watt or less since 1997. Australia, however, is *requiring* all electrical appliances to reduce standby power requirements from two to 25 watts today to one watt or less by 2010.

CSCI estimates that the measures it has proposed could reduce the annual electricity consumption of computers by 75%, allowing consumers to recoup the $20–$30 cost per system in lower electrical bills in less than one year.[106] If these solutions could be applied to other electronic devices with similar energy savings, global electricity consumption could be cut meaningfully.

A study by the Natural Resources Defense Council (NRDC) and Ecos Consulting indicates that nonactive modes of operation account for about 25% of the electricity consumed by electronic devices. The Lawrence Berkeley National Laboratory (LBNL) found that up to 90% of this power is wasted because of inefficient power supply design and unnecessarily energized components.[107]

LBNL indicates that significant reductions are possible largely by replacing inefficient linear power supplies with smarter switch-mode power supplies and by replacing standard switch-mode supplies with high-efficiency switching supplies. NRDC/Ecos data suggest that globally, 3 billion power-supply units are sold per year.[108] Unit sales are about evenly split between linear and switching supplies.

Linear power supplies are sometimes called "energy vampires" because they use an antiquated process technology that requires many turns of copper wire to convert 50/60 cycle AC grid power into lower-voltage DC device power. Also, they cannot recognize when a device has been inactive and, therefore, cannot switch into standby mode to reduce power consumption.

Switch-mode power supplies, by contrast, increase the AC frequency from 50/60 cycles per second to several thousand cycles per second. Although they generate power at a desired voltage in a series of brief pulses, they use only the number of pulses needed to meet the demand of a given load. In standby mode, they skip many pulses, reducing energy consumption. Companies active in manufacturing power supplies include Emerson Electric and Tyco. Among the firms producing the integrated circuits that improve the efficiencies of power supplies are Power Integrations and ON Semiconductor.

A voltage regulator automatically converts voltage supplied from the grid (or a battery) to the level needed by a device and maintains constant output voltage (within certain limits), despite changing line voltage or load current (or both). That is to say, a voltage regulator is used to provide voltage within normal operating parameters, which is critical because lower or higher voltage can cause function loss, overheating, erratic operation or component failure. In a typical computer, there are about 20–30 voltage regulators because most of the integrated circuits in the computer require one. The voltage regulator market is estimated to be about $7 billion per year. Companies in that market include Intersil, Linear Technology, Maxim Integrated, Monolithic Power, National Semiconductor and Texas Instruments.

Data Centers

It is difficult to calculate how much electricity data servers and centers consume globally, but the amount is large and growing. Companies are continually deploying new servers with faster processors, increased memory and greater storage, and thus require ever more power to operate and cool them. A typical server in 2000 consumed only 100 watts of power. The average server today consumes at least four times as much. Forrester Research estimates that a relatively small data center with 2,500 servers consumes enough electricity in one month to power 420,000 homes for a year. The US

106 Don Clark, "Computer Power Waste Targeted," *Wall Street Journal* (June 13, 2007)

107 Chris Calwell and Travis Reeder, "Power Supplies: A Hidden Opportunity for Energy Savings," Natural Resources Defense Council (NRDC) (Ecos Consulting: May 2002). See also online service http://www.energystar.gov/ia/partners/prod_development/downloads/power_supplies/powersupplies.pdf; Power Integrations

108 Calwell and Reeder, "Power Supplies: A Hidden Opportunity for Energy Savings"

DOE says that energy usage for a data center can be 100 times higher than for a typical commercial building.[109]

While energy costs today represent less than 10% of a corporate information technology group's budget, Gartner Group believes that the figure could rise to 50% in five years because of higher energy prices, greater reliance on digital forms of communication and increased data needs.[110] Indeed, some studies suggest that the annual cost to power servers will exceed the cost of the servers by next year. IDC calculates that the total power and cooling bill for servers in the US alone is $14 billion a year, and that if current trends persists, the cost could rise to $50 billion by the end of the decade.

Promising technologies that could significantly reduce the power requirements of data centers are automatic computing, multicore processors and virtualization.

Automatic computing would provision servers and schedule workloads using preestablished business rules that can reduce energy requirements. During periods of light activity, for example, applications could be automatically directed to one server so that others could be turned off. Additionally, some industry observers predict that increased data-center automation will enable firms to separate physical computing from the management of IT services, such that data centers could be relocated to locations with relatively low-cost power.

Multicore processors, which combine at least two processors into one package, enable firms to consolidate many small servers on to fewer, but better-utilized, systems, which also reduces power consumption.

Virtualization enables several applications to run on a single machine. By aggregating workloads onto fewer, more highly utilized servers and storage devices, firms can reduce the number of servers that they require and thus cut their power consumption. While this technology is still nascent and of limited applicability, in time it may allow IT managers to optimize their entire firm's processing power. BT recently deployed this technology to consolidate over 1,500 servers into about 100, which reduced its annual electricity bill by over $1.2 million. According to VMware, a virtualization leader, firms that consolidate servers by running multiple applications can reduce hardware, power, cooling and floor-space requirements by 50%–70%, while increasing service levels.

Additional electrical efficiency gains in computing and other electronic devices may be possible with the advent of smaller, faster and more efficient microprocessors and power chips, and advanced display and backlighting technologies. At this juncture, the timing, potential energy savings, cost to end users and potential providers remain unclear.

HVDC Transmission

Most of the electric power generated globally is transmitted and distributed using high-voltage alternating-current equipment, with line losses of 5%–10%. Changing to high-voltage direct-current (HVDC) transmission lines would reduce line losses to 3%–8%, because direct current does not oscillate. The switch would also make it easier to integrate renewable generation into the grid and to create interconnections among grids, which could help prevent blackouts.

There are numerous benefits of HVDC for renewable-energy sources, such as solar and wind. While fossil fuels can be transported to other power plants located closer to population centers to reduce electrical transmission distances, sunlight and wind cannot be transported: Only the electricity made from them can be moved. Therefore, electrical transmission and distribution efficiency are much more important to the overall efficiency of renewable energy. The largest sources of renewable energy tend to be far from the urban and industrial centers where electricity is used; as a result, efficient, long-distance transmission is crucial to project economics.

HVDC technology also allows rapid and accurate control of power level and direction, so it can compensate for the fluctuations in power flow from renewable sources that could otherwise disrupt the reliability of the electrical grid. For similar reasons, HVDC can also be used to interconnect separate power systems, joining AC with DC systems, and AC with AC.

HVDC lines cannot be overloaded, so the technology enables full power-flow control. Thus, HVDC allows power to be traded between independent power grids, while isolating failures, compensating for voltage instability and preventing widespread blackouts, according to ABB. HVDC also requires fewer transmission lines.

HVDC's drawback: Most power generated is AC, and most homes, offices and industrial plants use applications that

[109] Jessica Twentyman, "The Next Big Wave of Spending on IT," *Financial Times* (May 20, 2007). Forrester also claims that servers use about 30% of their peak electricity consumption while sitting idle (www.vmware.com).

[110] Ibid.

are powered by AC motors. Thus, HVDC lines require converters that transform the power from AC to DC at the plant, and then back to AC at or near the point of use. The need for this conversion makes HVDC economically attractive only for long-distance connections, typically over 600 kilometers (373 miles) for overhead lines and over 50 kilometers for underwater cables, ABB says. The main limiting factors for the growth of HVDC infrastructure are the preexisting AC facilities and the reluctance to replace functional equipment if it is not totally necessary. Thus, it may catch on fastest in rapidly growing emerging markets, such as China and India, with less sunk investment in AC infrastructure. Ultimately, growth in renewables and need for better grid interconnects are likely to spur widespread growth in HVDC transmission.

HVDC was developed by ABB over 50 years ago to increase the efficiency of power transmission over long distances. ABB completed the first HVDC link in 1954. It has supplied over half of the world's HDVC converter stations to date and has 50 projects commissioned or under construction today. The total size of the HVDC market is now estimated to be about $1 billion. ABB, Siemens and Areva collectively represent 75%–80% of the HDVC market, Société Générale estimates. Market growth is estimated to be about 10% per year.

Superconductors

Superconductivity also has potential to boost the efficiency of electricity transport. Copper wire, the traditional material used to transport electricity, retains some magnetic resistance even when cooled to subcritical temperatures. The resistance typically leads to heat dissipation, wasting energy in transmission and distribution.

Electric current flowing through a superconducting material meets no resistance when the material is cooled below its critical temperature. Once the material crosses this temperature threshold, paired electrons form a single quantum state that assists other electrons in passing through the same region without resistance. As this occurs, electric current flows without transmission loss.

The temperatures required for superconduction vary with the conducting material. They typically range from –269°C for niobium-titanium to –196°C for a ceramic composite known as BiSCO (bismuth strontium copper oxide). Superconductivity also occurs in materials such as tin, aluminum, metal alloys and doped semiconductors, but not in copper or gold.

Conceptually, superconductivity is the Holy Grail for electricity transmission. In practice, it remains in early demonstration stage. Today, superconducting cables are typically 10 to 15 times more expensive than traditional transmission cables. They also carry an added operating cost for keeping the system at the extremely low temperatures required. The key metric is how much it costs to move a volume of electricity a given distance. It is generally argued that for superconductors to be competitive in power transmission applications, the cable would have to sell for $10 per kiloampere meter. They are at least $100 per kiloampere meter more expensive than that today.

Superconducting cables are also much more complex and brittle than copper wire: They are generally made out of ceramic chemical compounds, coated with metal alloy substrates and surrounded by liquid nitrogen—the coolant—within a thermal isolation vacuum layer. Much heavier than copper transmission cables, superconductor transmission cables must be buried underground.

The market opportunity for superconductor transmission is most promising in urban corridors that need large volumes of power and have high-priced real estate. In such areas, it is also often difficult to install additional conventional underground copper cables because the existing underground corridors carrying power distribution cables are filled to capacity; adding new conduits would require expanding or securing new corridors. Superconductors that operate at the temperature of liquid nitrogen or higher are considered "high temperature" superconductors (HTS). The superior performance of HTS cables may eventually help relieve electrical grid bottlenecks. HTS cables can carry 150 times as much electrical current as comparable-size copper cables and conduct up to 10 times the power. They are easier to install, more reliable and more secure.

But the technology is still young. There are only two HTS cables operating in the live grid today, both in the United States: One is in Columbus, Ohio, which utilizes American Superconductor's first-generation HTS wire; and one is in Albany, New York, which utilizes first-generation HTS wire manufactured by Sumitomo Electric Industries in Japan. Other companies, such as Furukawa Electric, Nexans and Zenergy, are actively engaged in commercializing the technology. ■

ENHANCING THE EFFICIENCY OF TRANSPORTATION

The transportation sector generates 21% of CO_2 emissions today, primarily by burning fossil fuels in internal-combustion engines. Only a small part of the sector, mainly trains, is electric-powered. Nearly 70% of the CO_2 emissions from the transportation sector come from road transport: light-duty vehicles, buses and medium- and heavy-duty trucks. Our earlier research showed that there is a significant opportunity to reduce carbon emissions by improving the fuel efficiency of such vehicles by shifting to hybrid electric power trains.[111]

The typical full-hybrid vehicle available today has an electric motor powered by a large battery that is recharged from the hybrid's internal-combustion engine and by recapturing energy from braking. It reduces carbon emissions primarily by improving fuel efficiency, which reduces the amount of gasoline or diesel burned by the engine to perform a specific task (such as travel from home to work and back).

But the truly transformative potential of hybrids comes from the next generation: the plug-in hybrid vehicles that automakers are now working to commercialize. Plug-ins would have batteries that could be recharged by plugging into the electric grid, just like the batteries for laptop computers and mobile phones. While plug-in vehicle batteries may hold only enough electricity to power 40 miles of travel before recharging, the majority of car owners drive less than 40 miles a day when going about their ordinary routines, driving to and from work or school and doing errands. On a typical day, plug-in owners could thus rely completely on the electric battery (recharged overnight in their garage) and not use their gasoline- or diesel-burning engines at all. On the occasional longer trip, however, plug-in owners would use the engine to drive for many hours without stopping to charge the battery. We estimate that plug-in hybrid electric vehicles on average could get 75–100 miles per gallon of gasoline, or better.

Thus, plug-in hybrids could make road transportation largely, if not exclusively, reliant on the electric grid, rather than gasoline or diesel fuel. Since few electric plants now burn oil, plug-ins would break oil's stranglehold on the transportation sector and, therefore, the economy.

Plug-ins would also shift most, if not all, of the carbon emissions associated with road transport from hundreds of millions of tailpipes to a few thousand power plants. This shift would make cleanup of transportation-related carbon emissions significantly easier.

The Case for Hybrid Vehicles

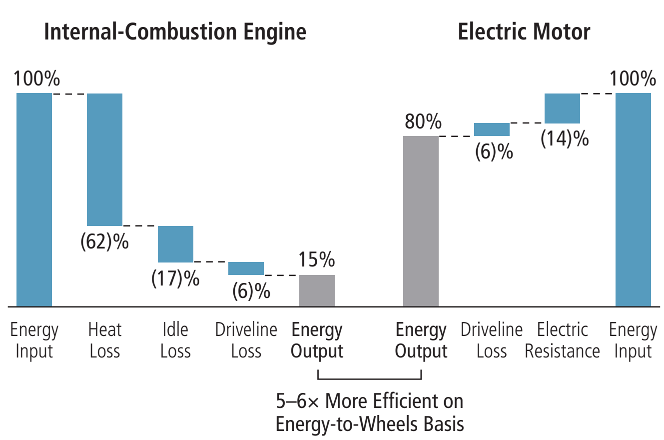
The internal-combustion engine, while a breakthrough in its day, is very inefficient: Only 15% of the energy inserted into the average vehicle is used for propulsion or powering accessories. The rest is wasted: 85% of the energy that goes into the vehicle is lost to heat, idling or driveline loss (*Display 79*). In addition, about half of the 15% of energy used for propulsion is wasted in braking, cutting the vehicle's energy efficiency to just 7%–8%. This inefficiency has been accepted for over a century because oil was plentiful and relatively cheap and because the internal-combustion engine offers high performance. Most cars today have 200–500 horsepower engines, although they rarely need that much power and it is very inefficient to keep large engines idling at a traffic light or cruising at low speeds.

By contrast, a vehicle powered only by an electric motor loses only 20% of its energy intake. It is five to six times more efficient than a vehicle with an internal-combustion engine. The only drawback has been the limited range of travel possible between battery charges. Hybrids solve that problem.

Hybrid vehicles, as their name implies, have both an internal-combustion engine and an electric motor, both of which can be used to move the car. Hybrids rely on

Display 79

Electric Motors Are More Efficient than Mechanical Engines



Source: Toyota Motor, US Environmental Protection Agency and AllianceBernstein

[111] Raskin and Shah, "The Emergence of Hybrid Vehicles"

Display 80

Hybrids Are Far More Attractive than the Alternatives

Factor	Hybrid (Gasoline)	Diesel	CNG*	Flex-Fuel	All Electric
Fuel Economy	High	Medium	Low	Low	High
Performance (acceleration)	High	Medium	Low	Medium	Medium
Emissions/Air Quality	High	Low	Medium	Medium	High
Model Choice/Flexibility	High	Medium	Low	Medium	Low
Convenience (range, refueling)	High	Medium	Medium	Medium	Low
Load Capacity	Medium	High	Low	Medium	Low
Initial Cost	Low	Medium	Low	High	Low
Cost per Mile	High	Medium	High	Low	High
Representative Model	Toyota Prius	VW Jetta	Honda Civic	GM Monte Carlo	Toyota RAV4 EV

High
Medium
Low

**Compressed natural gas*
Source: AllianceBernstein

the engine when it is most efficient, during high-speed travel and acceleration. They use the motor during low-speed acceleration and low-speed cruising, when the engine is not as efficient. Fuel economy is improved, and emissions are reduced whenever the electric motor is used.

Hybrids also improve fuel economy because they enable use of a smaller, more efficient engine without sacrificing performance: The motor can supplement the smaller engine's power to simulate a larger, more forceful engine. Furthermore, the engine totally shuts off when the car is stopped, eliminating wasted energy from idling. Finally, the hybrid's battery is charged from the energy that is typically wasted during braking, as well as from the engine.

The car switches between the two systems by itself: The driver does not have to do a thing. The basic driving experience is the same, with no need for special instructions or special refueling stations.

The transition to hybrid power is under way. Many analysts expect there to be more than 50 hybrid models on the road by 2010, when virtually every major automaker will have launched a hybrid vehicle. These models will span most vehicle classes, from subcompact to midsize sedans and full-size sport utility vehicles (SUVs).

These models are being planned, designed and built because hybrids offer the best combination of fuel efficiency, performance, convenience and emissions (*Display 80*). The only metrics for which hybrids are not best in class are load capacity and price. Diesel engines have greater load capacity, particularly at low speeds, which is important for pickup trucks, but not for most cars or SUVs. In time, diesel hybrids are likely to emerge to provide the greater load capacities that pickup trucks and larger trucks require. Hybrid technology can incorporate many different fuels, as well as advancements in other automotive technologies.

As for price: Hybrids cost manufacturers $3,200 to $4,000 more to build than comparable conventional vehicles.[112] Today, they pass most of that cost along to consumers.

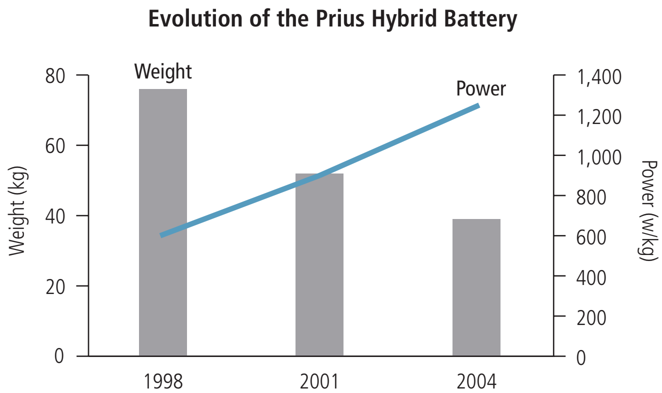
Hybrids are rapidly improving. Since the Prius, the longest-selling hybrid, was launched in 1997, both its fuel efficiency and acceleration time (0–60 miles per hour) have improved by over 30%. Its costs have declined by about 50% with each generation, despite the fact that it has increased from subcompact to midsize. The next generation, to be released in 2008 or 2009, is expected to have even better fuel economy and acceleration.

The Battery Challenge

The critical element for widespread adoption of hybrid vehicles, particularly plug-ins, is improving the quality of their batteries. Although hybrid batteries have become lighter (and hence cheaper) and more powerful in the last six years (*Display 81*), their high cost,

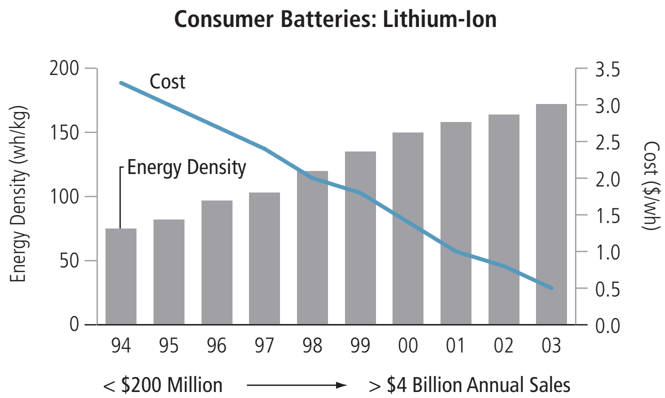
[112] The premium is for a midsize, full-hybrid passenger car (e.g., Toyota Camry Hybrid versus conventional Toyota Camry). In our earlier report, released in June 2006, we found the comparable premium to be $4,500–$6,000.

Display 81
Hybrid Batteries Are Already Getting Better and Cheaper



Source: Advanced Battery Council and Toyota

Display 82
Cost for Lithium Batteries Fell with Volume



Source: AABC (2005), AC Propulsion and AllianceBernstein

large size and limited performance (as measured by energy density and life) remain an impediment to faster market penetration. Plug-ins will need batteries capable of storing enough energy to power driving at least 40 miles a day to be worthwhile for the average car owner. Today's hybrid vehicles have nickel metal hydride batteries not capable of that range of travel between chargings. Next-generation hybrid vehicles will likely employ lighter, more powerful lithium batteries with the required capacity.

Lithium batteries are now used in many consumer electronic devices, such as laptops and mobile phones, which has allowed them to benefit from economies of scale: As the market for these batteries increased from $200 million to $4 billion, the cost per unit came down about 85% although their energy density (or, practically speaking, use or talk time before recharging is required), tripled (*Display 82*). We expect lithium batteries for hybrids to emerge soon and follow a similar cost curve, although safety issues may still have to be addressed.

Lithium batteries with certain designs and chemistries have exploded, leading to safety recalls for consumer-electronic batteries, including some well-publicized incidents with Sony, Apple and Dell laptops over the past year. Press reports suggest that safety concerns on the part of Toyota's executives may delay the introduction of lithium batteries in the next-generation Prius, originally due in 2008. Several other automakers, however, continue to state confidently that lithium batteries are safe for auto applications, and they will offer them in a year or two. We think that in time, chemists will improve lithium batteries to such a degree that they will become the standard power source for hybrids and plug-in hybrids.

The Transition to Hybrids

It is widely—but wrongly—believed that the auto industry changes slowly. In fact, many new technologies have been incorporated into vehicles fairly rapidly. Air bags were incorporated very fast because they were required by law. Desirable features such as front-wheel drive, fuel injection and radial tires were also adopted relatively quickly: Within 10 years of introduction, over 50% of new vehicles sold had these features.

Our research suggests that the most comparable analogy to hybrid vehicles is the introduction of the common rail diesel system in Western Europe in 1997, which benefited from both regulatory and technological advantages. European regulatory authorities favored diesel cars with lower taxes at the pump and point of sale. So when automakers introduced the common rail diesel, which improved fuel efficiency and performance, and reduced emissions of various pollutants, the new technology rapidly gained market share. In 1997, diesels represented only about 20% of new vehicles sold in Western Europe. A decade later, their share of new vehicles sold has climbed above 50%.

Similarly, we expect that market-share gains for hybrid vehicles will be accelerated by regulatory efforts under way around the world to increase fuel economy standards, enforce stricter limits on greenhouse-gas emissions—particularly for diesel cars and trucks—and promote clean air.

The Impact on Emissions

To estimate the impact of hybrids on CO_2 emissions, we used an approach similar to the one we used to estimate the impact of changes in power-generation technology: We looked at a base case, without the new technology, and then forecasted what we believe is a reasonable—and, indeed, likely—rate of adoption of hybrid vehicles.

Our base case is the IEA/SMP model,[113] which assumes that hybrid vehicles remain a very small percentage of the vehicle base. The IEA/SMP estimates that in 2030 the global fleet of light-duty vehicles would number 1,289 million, travel on average of 9,576 miles per year and have average fuel efficiency of 25.1 miles per gallon. This global fleet would emit a total of 4.5 gigatonnes of CO_2 per year.[114]

But if hybrids and plug-ins grow as rapidly as we expect, by 2030 the global fleet of light-duty vehicles would include nearly a billion hybrid vehicles and only 365 million conventional light-duty vehicles (*Display 83*). Recharging the 924 million hybrid vehicle batteries off the electric grid would likely increase global electricity demand by about 1.9 trillion kilowatt-hours per year, because we assume that 5,575 miles per vehicle, or 50% of the estimated annual driving of 11,150 miles, will be achieved using electric fuel at a rate of roughly 2.7 miles per kilowatt-hour.[115] We expect the annual driving of hybrid users to be higher than the baseline figure because, in our estimation, people who drive a lot will be more likely to purchase hybrids. Assuming the mix of electric generation in our abatement model (which includes extensive use of CO_2 sequestration technologies), we estimate that meeting this incremental electricity demand would add 0.4 gigatonnes of CO_2 emissions per year from the power sector.

Of course, hybrids and plug-ins would still have gasoline (or diesel) engines. We assume that hybrids and plug-ins rely on their engines half the time. Also, since they have smaller engines and use motors for supplemental power, we estimate that when their engines are in use, these vehicles will get average fuel efficiency of 31 miles per gallon (24% more than in the baseline projection). Thus, hybrids and plug-ins would continue to consume enough petroleum-based fuel to generate 1.5 gigatonnes of CO_2 a year, for total CO_2 emissions by the hybrid fleet of 1.9 gigatonnes. The 365 million conventional vehicles still on the road, meanwhile, would generate another 0.7 gigatonnes of CO_2 in 2030, bringing total CO_2 emissions by light-duty vehicles to 2.7 gigatonnes. While the incremental electricity demand by plug-in cars and light trucks would increase projected electricity demand in 2030 by about 7%, they would reduce global oil demand from these vehicles by 50% and total oil demand by over 13%.

Display 83

Adoption of Hybrid Vehicles Could Also Reduce CO_2 Emissions

	2030E			
	AB Emissions-Abatement Case			IEA/SMP* Reference Case
	Hybrids	Non-Hybrids	Total	Total
Light-Duty Vehicle Stock (Millions)	924	365	1,289	1,289
Miles Driven per Year	11,150	5,592	9,576	9,576
Miles per Gallon	62.2	25.1	50.0	25.1
Annual Oil Use (Billions of Gallons)	165.6	81.3	247.0	491.8
Incremental Electricity Demand (Trillions of Kilowatt-Hours)	1.9	0	1.9	0
CO_2 Emissions (Gigatonnes)				
– from Oil	1.5	0.7	2.3	4.5
– from Electricity	0.4	0	0.4	0
– **Total**	1.9	0.7	**2.7**	**4.5**

**Assumes hybrids achieve 50% driving from plugging into the electric grid and carbon intensity of power generation is 0.21 tonnes per megawatt-hour. In its reference case, the IEA assumes hybrids will account for less than 1% of the light-duty vehicle stock by 2030 and have an average mpg of 35. We adjusted the mileage assumptions in the IEA/SMP model to reflect subsequent disclosures from IEA staff.*

Source: IEA/SMP and AllianceBernstein

Thus, we expect deep market penetration by hybrid vehicles, including strong penetration by plug-ins, to reduce annual CO_2 emissions by the global fleet of light-duty vehicles from 4.5 to 2.7 gigatonnes, or 41%. The absolute emissions reduction will be even greater if, as we expect, hybrid technology also becomes widely used for buses and medium- and heavy-duty trucks. Hybrid buses are already used in New York City and San Diego. Hybrid delivery trucks (for example, Federal Express and UPS) and hybrid garbage trucks are in prototype.

113 The IEA/SMP model refers to the joint work by the IEA and the World Business Council on Sustainable Development's Sustainable Mobility Project (SMP) team in 2004.

114 We adjusted the IEA/SMP model on miles traveled to reconcile its output with the IEA's *World Energy Outlook*, 2004 and subsequent disclosures by IEA staff.

115 Recent research suggests that the actual rate of electricity consumption in the GM Volt could be 5 miles per kilowatt-hours.

We assume that 65% of medium- and heavy-duty trucks will be amenable to hybridization. If market penetration in this 65% is similar to the penetration we expect in the light-duty vehicle market, then by 2030 emissions due to oil burning from all modes of transportation would fall from 10.3 gigatonnes to seven gigatonnes. But these hybrid vehicles would require an additional 2.9 trillion kilowatt-hours of electricity. Even with the relatively clean electric power fleet that we expect to be in place, the incremental electric demand from hybrids would result in 0.61 gigatonnes of additional CO_2 emissions. In total, we expect that by 2030, efficiency advances in road transportation will reduce annual CO_2 emissions by 2.7 gigatonnes.

As discussed on pages 64 and 65, we expect the adoption of electrically efficient devices for motor, lighting and electronic applications to result in a 10% reduction in electricity demand. Under our forecast for CO_2 emissions by the global power fleet, by 2030 a 10% reduction in electricity demand would reduce annual CO_2 emissions by 0.62 gigatonnes.

In sum, we expect adoption of energy-efficient technologies in all sectors to reduce annual CO_2 emissions by 3.3 gigatonnes, an 8% reduction when compared with business-as-usual emissions of 42.9 gigatonnes. Thus, improving energy-efficiency will contribute to reducing emissions meaningfully, but will not be large enough to meet global requirements.

Biofuels' Potential Impact

Transportation-related carbon emissions can also be reduced by changing the fuel, rather than the technology. Most notably, biofuels such as ethanol and biodiesel can be used alone or mixed with gasoline or diesel (respectively) to cut fossil-fuel consumption and thus cut CO_2 emissions from cars, trucks, buses, ships and even airplanes.

More than 80% of the biofuel now produced is ethanol made from sugar crops (primarily sugarcane, beets and sweet sorghum) or starch crops (primarily corn, cassava and wheat). Sugar and starch crops each have about 40% share. Research is also under way to develop and commercialize ethanol produced from nonedible cellulosic plant matter such as switchgrass and wood chips. The other 20% of biofuel produced is biodiesel made from animal fats and a wide range of vegetable oils, such as canola, palm, rapeseed, soy and jatropha.[116]

Although petroleum still accounts for nearly all transportation fuel, global biofuel production surpassed 670,000 barrels per day in 2006, equivalent to about 1% of total global oil consumption for transportation.[117] Biofuel production has doubled since 2001. It is likely to continue to grow rapidly in the near term as producers and consumers respond to higher conventional fuel prices, government mandates and subsidies. The emergence of new technologies and expansion of the production, storage, distribution and refueling infrastructures needed to support biofuel use will also encourage near-term demand growth.

In our opinion, biofuels are largely a political issue. Many governments around the world are actively promoting biofuel use in order to reduce reliance on imported oil, as well as to support domestic agriculture. Protecting the environment or curbing greenhouse-gas emissions is likely a secondary concern, since there are many more effective ways to achieve this objective. Nonetheless, in his 2007 State of the Union address, US President George W. Bush called for using biofuel to replace nearly 15% of the petroleum that the US will use for transportation, by 2017. Similarly, the European Union has mandated that 10% of transportation fuel in member nations be replaced with biofuels by 2020. It is recommending a 25% target by 2030. Japan, China, India and several other countries have adopted or are considering similar guidelines. Taking these mandates into account, the IEA projects that biofuels will account for about 3% of transportation fuel globally by 2030.[118]

Biofuels can be blended with gasoline or diesel in proportions ranging from almost 0% to nearly 100%. The resources required to blend biofuel in a 10% (or less) fuel mix would be relatively modest, and the cost would be low because at these levels the existing petroleum infrastructure can be utilized. However, the oil-savings and emissions-reduction benefits would also be small. As a result, much of the discussion on using biofuels to enhance energy and climate security is focused on an 85% mix, or on using biofuels alone.

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116 Coal has also been used as a feedstock to produce a liquid fuel for transport, using coal to liquids (CTL) technologies. While CTL output is sometimes referred to as a biofuel, coal is not a recently living organic material like the other feedstocks mentioned; it is made from plant matter that died millions of years ago. While CTL is an interesting way to reduce oil consumption and thereby enhance energy security, it would considerably worsen CO_2 emissions.

117 Worldwatch Institute, "Biofuels for Transportation" (June 2006)

118 IEA, *World Energy Outlook*, 2006

Display 84

With Unlimited Land, Sugarcane and Jatropha Are Best Fossil-Fuel Substitutes

Fuel Type	Production Cost ($/liter*)	Emissions Reduction (%)†	Fossil Fuel Input as % of Energy Output‡	Land Use (liters*/hectare)
Ethanol				
Gasoline	$ 0.34	0%	100%	NA
Corn	0.4	18	82	1,500–3,000
Sugarcane	0.23–0.29	91	59	3,000–6,000
Cellulosic	0.71	88	12	4,500–6,000
Bio-Diesel				
Diesel	0.41	0	100	NA
Palm Oil	0.54	70–100	20	3,000
Rapeseed	0.87	21–38	26	1,200
Jatropha	0.40–0.65	100	14	3,000

**Liters measured on an energy-equivalent basis*
†Reduction in greenhouse-gas emissions per kilometer traveled by replacing fossil fuels with biofuels in conventional vehicles, over the full production cycle of the biofuel
‡Fossil-fuel input measured over production, distribution and retailing processes
Source: Argonne National Laboratory, Biopact.com, Center for American Progress, Center for Jatropha Progress, IEA, "Biofuels for Transport" and "Energy Technology Essentials: Biofuel Production," IMF and World Economic Outlook, *2007*

The Varieties of Biofuels

To evaluate the carbon-emissions benefits of biofuels now available or in development, we looked at the fossil-fuel input required to produce them and the CO_2-emissions reduction offered relative to gasoline or diesel. We also looked at their cost of production and land-use efficiency.

On these scores, the varieties of biofuels vary widely. The fossil-fuel energy input required to produce a unit of biofuel ranges from 12% to 82%, and the potential CO_2-emissions reduction ranges from 18% to 100% (*Display 84*). On both of these metrics, cellulosic ethanol and jatropha-based biodiesel appear far superior to the alternatives; corn-based ethanol is the least attractive. Palm oil also scores relatively well, and sugarcane scores high on CO_2 reduction but less high on fossil-fuel energy required. Sugarcane and cellulosic ethanol also have an advantage in yield per square meter of land used. Since sugarcane-based ethanol has the lowest production cost without subsidies, it is the most promising biofuel in the near term.

The principal drawback of sugarcane-based ethanol from a policy perspective is that more widespread use could eventually contribute to food-price inflation, since sugar is found in a wide variety of foods. Right now, the principal barrier to greater market penetration of sugarcane ethanol is US and European import tariffs on sugarcane ethanol produced in Brazil, which reflect political pressures from domestic agricultural interests.

Cellulosic ethanol may become a more compelling alternative over the long term as the cost of production declines with commercialization and economies of scale. The feedstock is not a food source and can be grown on land not suitable for agriculture.

The Demand Outlook

In the near term, more people may buy vehicles capable of running on biofuels if the price of the vehicle and the fuel are right, and if the fuel is convenient to obtain and doesn't impair performance. Vehicle price is not much of an obstacle: Engines capable of running on traditional fuels as well as biofuels (in 0%–100% blends) cost only a few hundred dollars more than traditional engines.

Fuel prices must be adjusted for the lower energy-density of biofuels to be competitive. Mileage from a gallon of ethanol is about 30% lower than mileage for gasoline, and mileage for biodiesel is about 10% lower than that of diesel. Thus, we would expect consumers to embrace biofuels only if the price per gallon at the pump is 10% or 30% cheaper than for the comparable fuel. In Brazil, where over 70% of new cars sold can run on gasoline or ethanol, ethanol sells at a discount roughly equivalent to its mileage penalty. Elsewhere, governments will likely have to subsidize the price until producers achieve lower costs through new technologies and scale.

As for convenience, automakers often install larger fuel tanks in flex-fuel vehicles so that the lower energy density of the biofuels does not impair the range of travel per tank. But many more refueling stations will be needed along with other supporting infrastructure before flex-fuel vehicles become attractive. Only 1,200 of the nearly 170,000 refueling stations in the US offer E85, an 85% ethanol blend. The US DOE estimates that about 55,000 refueling stations would need to offer E85 to make it attractive for the mass market.

The cost of retooling a refueling station is estimated at about $60,000, so the system cost for retrofitting the minimal number of refueling stations would be about $3 billion for the US alone. Additional costs would include procurement of agricultural resources, research and development, and the construction of plants, distribution and storage facilities. We have not seen estimates for these costs, but it is likely that they are a multiple of the cost of retrofitting or retooling the fueling stations.

In addition, the biofuel produced will likely need to be subsidized at the pump for at least several years. According to a study by the International Institute for Sustainable Development, US biofuel subsidies will cost $8–$11 billion annually from 2006 to 2012.[119]

Performance has historically been an issue with biofuel vehicles: Acceleration times were much longer than for comparable gasoline or diesel vehicles. That may change. In recent months, Saab has announced technological innovations that enable biofuel vehicles to accelerate faster than conventional models. Using sugar-based ethanol in an 85% or higher blend, along with advanced turbocharging technology and engine-management systems, the Saab 9-5 BioPower takes advantage of bioethanol's higher octane rating to deliver 20% more horsepower and 16% greater torque. The result: It accelerates from 0 to 100 kilometers per hour (equivalent to 0–62 miles per hour) in just 8.5 seconds, compared with 9.8 seconds when running only on petrol.[120] It remains unclear when this prototype vehicle will be available for purchase, what it will cost, the number of models that will use the technology and whether it will be licensed to other automakers.

Another way to overcome the performance issue is to use biofuels in hybrid and plug-in hybrid vehicles. The acceleration time in these vehicles will largely depend on their electric motors, not their fuel. Use of biofuel would add to the oil savings and emissions reductions achieved by hybrid electrical vehicles.

Limited Opportunity for Biofuels

In the near term, the growth of biofuels could be limited by the availability of land, water and other resources, given competing demands for food production. Over the long term, however, our analysis suggests that the case for biofuels will ultimately be undermined by growing market penetration by hybrid electric vehicles, which are likely to provide a more convenient and cost-effective way to reduce reliance on fossil fuels.

Each gallon of oil replaced by cellulosic or jatropha ethanol reduces carbon emissions by about 90%–100%, so each 1% shift of transportation fuel to biofuel in 2030 would reduce emissions from the transport sector by 1% at best. Since transportation accounts for 20% of the total emissions, a 10% shift in transport fuels from petroleum to the most attractive biofuels would reduce total global carbon emissions by 2%.

But we believe that biofuels gaining a 10% share of global transport fuels by 2030 is a stretch, and levels beyond that are unlikely. The technological breakthroughs, particularly on cellulosic ethanol, as well as the necessary infrastructure build-out, will take significant time. During the same period, we expect automakers to make impressive strides in the fuel efficiency, performance and cost of advanced batteries and hybrid vehicles; plug-in hybrid technology would emerge soon after. We expect hybrids to be cheaper (largely because of efficiency improvements that will reduce operating costs) and more convenient for most users than vehicles that run on either traditional fuels or biofuels. They will also require far less infrastructure development.

In short, we expect mass penetration of hybrid vehicles, particularly after plug-ins are developed, to forestall mass penetration of biofuel vehicles. Biofuels are simply an inferior way to reduce dependency on oil. We believe that biofuels are more likely to provide incremental emissions reductions if incorporated within hybrid vehicles than if used as an alternative in their own right. ■

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[119] Cited by Simon Powell et al., "Global Biofuels, Chomp! Chomp!: Fueling a New Agribusiness" (CLSA, April 2007)

[120] http://www.greencarsite.co.uk

Macroeconomic Implications

For the most part, the macroeconomic impact of efforts to reduce greenhouse-gas emissions will be benign. Many jobs will be created in relatively high-wage sectors as new nuclear plants are built, high-voltage transmission lines are laid across the globe to connect remote wind farms and concentrated solar-power projects to the grid, and pipelines are built to transmit CO_2.

Electricity prices are likely to go up almost everywhere, encouraging adoption of more efficient systems and raising energy productivity, but imposing an undeniable burden on electricity consumers. A higher portion of household disposable income will go to paying for electricity, but the overall impact will likely be mild: For the most part, electricity consumes a relatively small percentage of disposable income. Even a significant percentage increase in electric prices will likely have a much lower impact than, say, a tax increase.

For countries seeking to attract industry, abundant natural resources or a cost-competitive energy/electricity infrastructure (such as one bolstered by an advanced fleet of nuclear reactors) will become increasingly important. Iceland, for example, has been actively marketing its cheap geothermal power to attract industry, and with it jobs and tax receipts. Some electricity-intensive firms, such as Alcoa and DuPont, have already relocated operations abroad to gain access to cheaper electricity. Others are likely to follow suit. For companies deciding where to locate facilities, relatively cheap electricity may soon become as important a consideration as cheap labor.

The Chinese government, in particular, is keenly aware of this issue. It recognizes that in order to maintain its rapid economic growth, China will need both to build cost-competitive electric plants with significantly less CO_2 emissions and to expand its less energy-intensive, service-related industries. In fact, if China cannot transform its electric infrastructure, we would expect energy-intensive manufacturing to begin to relocate away from China, once considered the exemplar of low-cost manufacturing.

Other shifts will occur within countries. For example, regions within the US with relatively cheap power supplies may benefit from an influx of business and jobs. Internet companies such as Google, Yahoo! and Amazon are already moving their data centers to rural areas in Tennessee and Oregon with access to inexpensive nuclear and hydroelectric power.

As we noted in the beginning of this report, even the most vigorous and well-thought-out efforts to reduce greenhouse-gas emissions will only slow the accumulation of atmospheric CO_2. If the scientists are correct, mankind will still have to adapt to rising sea levels, reduced mountain runoff and violent weather events. Adaptation will likely be very expensive—as the Stern report detailed so painfully. Thus, even if the actions described in this report have beneficial macroeconomic implications, the reality is that they may help only to pay the bill for moving population centers, food production and other vital economic resources out of harm's way. ■

Investment Implications

The investment implications of climate change are fairly straightforward to identify, but that does not diminish their likely impact. The sheer magnitude of the spending required to significantly reduce carbon dioxide emissions will have major implications for many companies in a diverse set of industries.

The largest increases in capital spending and most significant technology shift will be in the electric-power industry. As one would expect, much higher levels of spending by utilities will be great news for manufacturers of generating equipment. We expect makers of nuclear equipment, clean-coal technologies, wind turbines and solar equipment—and their suppliers—to enjoy strong growth over the long term. In our view, however, the near-term prospects for solar energy are far less rosy than many investors seem to think. Indeed, we think that speculative interest in this segment has contributed to unjustifiably high valuations that are likely to correct.

Automotive batteries may be the single biggest product category to gain from efforts to forestall climate change. We forecast the market will grow from $9 billion today to well over $150 billion (depending on unit prices) by 2030.

Makers of pipelines, efficient motor systems, power semiconductors and hybrid vehicles should also enjoy strong demand growth as a result of the global effort to reduce carbon emissions. Coal-mining companies, their equipment suppliers, and rail and barge companies that transport coal should benefit from the increased long-term demand for coal from electric utilities.

Oil-field service companies and owners of partially depleted oil fields and unminable coal seams are likely to be secondary beneficiaries of the new need to safely inject and store vast quantities of CO_2. However, for most oil-related entities, any benefit from this new market is likely to be overshadowed by the perilous combination of decreased oil demand (resulting from widespread adoption of plug-in vehicles) and increased supply (as abundant quantities of CO_2 are used for enhanced oil recovery).

Other major losers will likely be companies that consume a great deal of electricity, if they cannot find ways to cut their electricity consumption or cheap sources of electric power, and if they cannot pass on the higher cost to their own customers. Aluminum and cement firms may be particularly vulnerable to such a margin squeeze or to competition from potential substitutes.

Private individuals, as well, will bear the burden of higher electricity prices: Electricity expense as a percentage of disposable income will rise faster than other costs. The impact will be somewhat ameliorated by the adoption of more efficient devices and efficiency standards for new construction, as well as by progressive electricity-pricing schemes.

A WORD OF WARNING

As we said at the outset of this report, regulations to control carbon emissions will impose significant costs to governments, businesses and consumers. The specific details of how these regulations are written may help determine the ultimate winners and losers. For example, a cap-and-trade program with emissions credits auctioned to the highest bidder would be significantly more expensive for coal-plant operators than a cap-and-trade program that grants emissions permits to existing emitters based on their current CO_2 emissions.

A key assumption throughout this report is that utilities will be able to recoup the higher spending levels necessary to transform their infrastructure. If, for political reasons, this assumption proves to be wrong, many utilities would face serious financial pressure.

Although many of the trends that we discuss will not take hold for several years, we have already seen many companies planning for the advent of strict regulation of greenhouse-gas emissions. Some are planning to capture new market opportunities; others are seeking to mitigate a looming risk to their traditional business. It is difficult to predict exactly when stock prices will begin to reflect these potential opportunities and risks. The market, however, is a terrific mechanism for discounting the impact of long-term trends. Sometimes stock prices reflect trends even before the trends are reflected in companies' business-planning decisions, let alone their financial statements. Therefore, investors who wait to include these factors in their financial analysis of equity investments may miss stock-price surges.

In this section, we detail how several industries are likely to be affected by efforts to curtail carbon emissions. We highlight the likely impact on their operations over the short term (one to five years), medium term (five to 10 years) and long term (beyond 10 years). *Display 85* summarizes our conclusions, rating the overall investment implications for each broad industry group from +++ (Highly Positive) to ––– (Highly Negative). A split rating for a given time period (such as +++/–––) means that the trend will be positive for some industry players and negative for others. The display also places the categories that gain most from emissions-reduction efforts on top, and those hurt most at the bottom. In the pages that follow, we list the categories alphabetically.

In the pages that follow, we name the major players in some industries that may benefit from (or be hurt by) these trends for representational purposes only. We are not recommending the purchase or sale of these stocks. These pages do not include detailed analysis of the likely impact of the expected benefit or loss on company earnings and cash flow. They also do not include the valuation analysis necessary to make an investment recommendation. We leave it to readers to perform the additional analysis required, if we have piqued their interest.

Display 85

Industry Winners and Losers

	Time Frame			
Category	**Short**	**Medium**	**Long**	**Comments**
Electric-Generating Equipment	++	+++	+++	Near-term growth spurred by spending growth in renewable energy, transmission and distribution, and smart-grid equipment. Significant demand acceleration in the medium to long term for nuclear and clean coal turbines, as well as services.
Energy-Efficiency Enhancing Technologies	++	+++	+++	A wide variety of firms will benefit from adopting energy-efficient solutions in transport and nontransport sectors. Automotive-battery and semiconductor companies may benefit the most. Providers of efficient motors, magnets and advanced lighting are also well positioned.
Engineering & Construction	+++	+++/–	+++	A prolonged period of heavy investment in power infrastructure will benefit E&C firms in the near, medium and long term. Over the medium term, project complexity and delays could be a minor impediment.
CO_2 Transport, Injection and Storage	+	++	+++	Strong demand growth creates a new opportunity for pipeline builders, owners and operators, and for oil-field service firms and companies with CO_2-handling expertise.
Electric Utilities	++/––	+++/––	++	Massive capital investments will be required in the short, medium and long term. Regulatory risk around cost recovery will persist in the near to medium term. Utilities with assets that are cost-competitive in the new environment will do best.
Transportation	++/––	+++/–––	+++/–––	Makers of fuel-efficient vehicles with low carbon emissions will see accelerating demand growth. Over the long term, hybrid electric vehicles will dominate; companies able to make the transition and their suppliers will win.
Commodity-Related	+/–	++/–	+++/––	Coal and uranium markets are largely in balance near term, with near-term risk to prices if economic growth slows. Medium to long term, accelerating demand growth from developing markets and new power plants will raise marginal production costs, benefiting companies with large low-cost reserves. Mining equipment and transportation companies will be secondary beneficiaries. Oil producers and refiners will be hurt by rising supplies due to enhanced oil recovery and by diminishing demand for oil from road transport.
Electricity-Intensive Industries	+/–	+/––	+/––	Negative impact over all time periods, although in the near term, energy-intensive cement, petrochemical refining and silicon-manufacturing firms will benefit from tight capacity and strong demand growth. Over the medium to long term, rising electricity costs will be a substantial burden. Industries may relocate to regions with low electricity costs and develop more energy-efficient processes.

Source: AllianceBernstein

CO_2 TRANSPORT, INJECTION AND STORAGE

ST +	MT ++	LT +++

Every CO_2-capturing facility will need to transport large volumes of CO_2 to suitable storage locations and inject the CO_2 into the ground or under the sea. Few power-generating companies, chemical firms or electricity-intensive manufacturing firms are equipped to perform these tasks. Thus, CO_2 transport, injection and storage represents a burgeoning market opportunity for capable third parties in the medium term and a high-growth market in the long term.

We expect global daily volume of CO_2 captured and sequestered to exceed 7 billion cubic feet (bcf) by 2015, approach 70 bcf in 2020 and hit 500 bcf before 2030.

Projecting the size of the infrastructure build-out is tricky. CO_2 pipelines are unlikely to carry their gases as far as natural-gas pipelines do: Utilities will likely build facilities near to storage sites, when possible. Additionally, CO_2 pipelines will have higher utilization rates than natural-gas pipelines because demand for natural gas is more sensitive to weather and commodity prices and is more subject to seasonal shifts. Broadly speaking, however, the infrastructure required over the next 25 years is likely to equal, and perhaps exceed, the infrastructure currently required for natural gas.

The primary beneficiaries of such an expansion will be **pipeline builders, owners and operators**. These companies currently profit by constructing pipelines and leasing their use to distributors of natural gas and other petroleum products. Although those pipelines are not amenable to use for CO_2, the companies that build them will certainly be willing to build dedicated CO_2 pipelines and use them to transport CO_2 from its source to its storage site once a market for such services develops.

In order to efficiently transport CO_2 by pipeline, the gas must be maintained in a supercritical state at pressure greater than 1,500 pounds per square inch.[121] The gas must be compressed when initially captured and, if the pipeline is very long, may need to be recompressed along the way. Companies that have previously provided these services for natural-gas transport are likely to gain new business from CO_2 pipelines.

Depending upon the regulatory environment, significant portions of pipeline development costs may go toward acquiring rights of way. Landowners, particularly those with space along existing rights of way, stand to gain as the transport infrastructure develops.

It is clear that transporting large quantities of CO_2 will require a tremendous infrastructure build-out. We expect global spending on CO_2 transport to reach $3 billion per year by 2020 and exceed $15 billion by 2030.

But transporting CO_2 is only half of the story. CO_2 injection and monitoring will also become an important market in the medium to long term. **Oil-field service companies** that have already demonstrated expertise at drilling and extracting hydrocarbons will be paid to drill and inject CO_2 into the Earth and to keep track of it once it is there.

Near-term CO_2 storage opportunities will arise near mature oil and gas fields. With high commodity prices, energy exploration and production companies are likely to assume the cost of CO_2 disposal because they can use the CO_2 to extract additional oil from declining or depleted assets. Companies that control access to the few existing natural CO_2 reserves are already developing regional enhanced oil-recovery (EOR) pipeline networks. These companies, with their demonstrated CO_2-related expertise, may find themselves well positioned to compete as full-service providers of CO_2 transport and sequestration over the long term.

Mineral-rights holders for mature or depleted oil fields and unminable coal beds will also benefit as these assets attain new value as enhanced recovery and storage sites.

We estimate that the market for injection and storage of CO_2 will reach $1 billion by 2015, $9 billion by 2020 and almost $80 billion by 2030.

+++	Highly Positive	–	Negative
++	Very Positive	– –	Very Negative
+	Positive	– – –	Highly Negative

[121] Gemma Heddle, Howard Herzog and Michael Klett, *Economics of Carbon Dioxide Transport and Storage* (MIT Laboratory for Energy and the Environment, August 2003)

COMMODITY-RELATED

ST +/–	MT ++/–	LT +++/– –

The vast expansion of nuclear power and higher coal requirements at carbon-capturing coal-power plant will significantly boost demand for both uranium and coal in the medium and long term.

Uranium- and coal-mining companies with large, low-marginal-cost reserves will benefit from long-term secular demand growth. In the short term, however, there is ample supply of both commodities to satisfy demand. Prices for coal, in particular, may weaken in the near term, as small, inefficient plants are shut down and replaced by larger, carbon-capture-ready plants that will be considerably more efficient until they are actually required to capture carbon dioxide.

As medium- and long-term demand growth materializes, however, benefits will ripple through the value chain: **Mining-equipment companies** will see order books expand for big-ticket items such as electric shovels, drills, draglines and supersize dump trucks. Companies specializing in **nuclear enrichment** will enlarge operations and build new facilities. The number of **nuclear-reprocessing facilities** will also likely increase as the industry gains scale globally.

Growth in demand for coal as CO_2 capture makes coal-power plants less efficient will likely increase demand for **railroad and barge transport** over the medium to long term. Some of the gains in coal transport, however, may be offset by new coal plants being located close to coal beds.

Among the sectors most vulnerable to the results of emissions-abatement efforts are oil producers and oil refiners. Electrification of road transport will significantly reduce demand for gasoline and diesel fuels. Meanwhile, oil supply may grow meaningfully as a result of enhanced oil-recovery efforts that boost output by flooding mature oil fields with CO_2. Although oil-field service firms may benefit from the expanded market for CO_2 injection, for the vast majority of the oil complex the twin trends of reduced demand and increased supply are likely to be detrimental.

ELECTRIC GENERATION EQUIPMENT

ST ++	MT +++	LT +++

We foresee trillions of dollars being spent on power-generation equipment between now and 2030, making the growth outlook for vendors and their supply-chain partners extremely robust in the short, medium and long term. In the short term, companies with exposure to fast-growing markets such as China, India, Russia and the Middle East should see strong revenue growth for traditional (non-carbon-capturing) equipment. In the medium to long term, new technologies and processes that either capture CO_2 or do not create it as a by-product (such as nuclear and renewable energy) should benefit from a robust investment cycle in all regions. In addition, new power-plant sites and the adoption of renewable-energy technology should spur significant investment in transmission and distribution infrastructure and smart-grid equipment.

Coal-Power Equipment

Traditional coal-power equipment makers are pursuing opportunities in clean-coal solutions. Most are working on their own technology initiatives or partnering with others to develop products and processes that reduce CO_2 emissions. In the short term, their R&D initiatives and demonstration projects will have little to no impact on earnings. In the medium to long term, however, sales of equipment for clean coal power will become material, displacing traditional coal equipment. We expect sales to accelerate as customers seek to comply with stricter carbon-emissions rules.

Furthermore, while many coal-power plants will be retrofitted, many older or smaller, inefficient facilities will simply be replaced with new plants using a new technology. This will create an opportunity for equipment makers to increase their share of total plant costs.

As detailed in the coal section of this report, **integrated gasification combined cycle** (IGCC) generators are among the best of the emerging clean-coal alternatives. For an equipment maker, IGCC creates an opportunity to capture about 40% of the plant value versus about 5% in a traditional coal plant: In addition to the steam turbines and generators that it provides for a traditional plant, the vendor can sell the utility gasifiers and related equipment, including gas turbines and heat-recovery systems. Over the long term, the gasifiers and gas turbines that come with IGCC also provide aftermarket-service opportunities.

Leading IGCC vendors include GE, ConocoPhillips, Siemens, Shell, Mitsubishi Heavy Industries and Southern Company. Leading companies focused on post-combustion carbon-capture retrofits for traditional coal technologies include Alstom, McDermott's Babcock & Wilcox subsidiary, Fluor and Foster Wheeler. Companies specializing in industrial-gas equipment and processes for IGCC plants and for oxy-fuel retrofits of pulverized-coal plants will also benefit in the medium to long term (see discussion of chemical industry on page 91).

Natural-Gas Turbines

In the near term, we expect strong growth for manufacturers of natural-gas turbines. Rapidly growing economies with ample gas reserves, such as many Middle Eastern countries and Russia, are adding gas-fired generation to meet their power needs. In the developed world, natural-gas-power plants offer a hedge against uncertain carbon regulation, since they can be built quickly and emit half as much CO_2 as coal-power plants. In the medium to longer term, we expect incremental growth in turbine sales to come from coal-based IGCC-power plants, rather than from traditional natural-gas plants. This change in end market will require modifications, but most turbine vendors are already working to adapt their offerings.

The dominant vendors of natural-gas turbines are GE, Siemens and Mitsubishi Heavy Industries. Future growth opportunities for gas turbines are heavily dependent on the success of the IGCC market.

Nuclear Equipment

In the short term, nuclear-equipment vendors and their suppliers will enjoy expanding order books and backlog growth that may soon lead to capacity bottlenecks. Critical components (such as the heavy forgings used to make reactor vessels) are in short supply. In the medium to long term, the industry should be able to meet prolonged demand growth by expanding organically or by licensing manufacturing specifications to third parties. Long term, nuclear vendors will benefit materially as the nuclear fleet grows and takes share from other sources of electric-power. Suppliers will also benefit from strong growth in demand for fuel service and maintenance. Of course, unforeseen changes in public sentiment could materially hamper the industry and cause order cancellations.

Westinghouse (now majority owned by Toshiba), Areva and GE/Hitachi are the three dominant nuclear-power vendors. They benefit from the high barriers to entry in this tightly regulated industry.

Photovoltaic-Power Products

Like many young industries, the solar industry is highly fragmented, with an array of vertically integrated competitors and specialized niche players. Supply chains have developed in jurisdictions with strong solar policies and incentives, creating a hodgepodge of markets in countries such as Japan, Germany, Spain, the US, China and South Korea. Early leaders like BP Solar, Sharp and Kyocera are now being challenged by well-capitalized upstarts such as Suntech, SunPower, REC and Q-Cells.

Today, **silicon production** and solar-cell installation are the most profitable parts of the value chain. The recent involvement of traditional semiconductor-equipment players, such as Applied Materials, shows that there is a substantial growth opportunity in providing tools and equipment to support solar manufacturing. It also suggests that manufacturing costs will continue to decline. How soon such declines will enable solar to provide electricity to the grid at a competitive price remains an open question. As long as governments continue to subsidize the industry, however, there will be robust demand for a product that is currently constrained by limited polysilicon and equipment supplies.

In the near term, all vendors will benefit from strong industry growth. However, as the silicon-supply shortage eases in the near to medium term, margins may tighten for companies throughout the value chain. This could be a turbulent time for the industry; significant consolidation is possible.

Over the medium to long term, the capital intensity of the production process is likely to increase. Producers are likely to establish specialized practices that make more efficient use of source materials, increase throughput and reduce labor costs. Higher capital requirements will raise barriers to entry and discourage other small players from entering the market. If the solar-power market continues to expand meaningfully, semiconductor titans such as Intel and Samsung could bring their significant experience and capital to the table as late, but powerful, contenders.

We also expect the **solar-installation market** to remain fragmented in the near term. Today, there is a shortage of qualified installers, and even sophisticated solar buyers with ample disposable income are subjected to a trying purchasing experience. Some of the difficulties reflect grid-connection policies, which vary substantially from region to region. In the medium to long term, we expect consolidation and standardization among installers. Installation may ultimately be dominated by a small group of well-established distribution networks much like those that now install furnaces, air conditioners and water heaters.

+++	Highly Positive	–	Negative
++	Very Positive	– –	Very Negative
+	Positive	– – –	Highly Negative

Wind-Power Equipment

The wind-power-supply chain is similar to that in solar, in some respects. Robust growth over the past few years has outpaced supply of critical components, such as gearboxes and nacelles, which house the gearbox and drivetrain. In the near term, we expect the wind-power-equipment industry to lack the materials and manufacturing capacity needed to keep up with global demand growth, which is estimated at 19%. Many vendors have already sold out their 2009 turbines. Market leaders such as GE, Siemens and Vestas are aggressively expanding capacity. In the medium to long term, we expect growth to slow as the best wind sites are occupied and more cost-effective carbon-emissions-reduction methods gain scale.

Transmission and Distribution

We expect capital spending on transmission and distribution (T&D) to grow in tandem with investment in power generation in the very near term. It should grow somewhat faster between 2010 and 2020 as US and European regulatory mandates for renewable-energy and grid stability lead to an investment surge. Massive additions of renewable-energy capacity require a transmission infrastructure capable of dealing with the siting, reliability and dispatching issues posed by these power sources.

Grid security concerns and shrinking capacity reserve margins in many countries and regions have led many regulators to provide developers with rights of way and to encourage new investment through favorable tariffs and incentives. Thus, the underinvestment in T&D infrastructure spending throughout the developed world in the 1980s and 1990s is now reversing.

Transmission and distribution spending will also grow with efforts to provide access to electric power to the quarter of the world's population, mostly in rural areas, that are now without it. In the Middle East and Africa, T&D spending is being stimulated by oil and gas revenues and the need to support the expanding energy infrastructure. China, India, Malaysia and the Philippines are expanding their T&D infrastructure rapidly. Russia, too, is committing petrodollar revenues to rural electrification.

Although there are hundreds of companies that provide this kind of equipment, these investments should benefit proven T&D vendors such as ABB, Siemens and Areva, which command 25%, 18% and 10%, respectively, of the global market.

Smart Meters

Managing the electricity that flows through the power lines is just as important as adding more power lines. The old saying that you cannot manage what you cannot measure is highly relevant in the electric utility industry. Smart meters allow customers to reduce demand when power markets are tight, and they help utilities to avoid adding expensive new capacity. Thus, smart meters are key to making production and use of electricity more efficient. In the short to medium term, we expect strong demand growth for advanced electricity meters—particularly those that offer two-way communication enabling demand response to real-time price signals.

Meters were once a low-growth business tied to new housing starts and replacements. They are becoming a high-growth industry, thanks to rising electricity prices, technological innovation and increasingly stringent environmental regulations that encourage replacements. In the long term, we expect growth to moderate, unless breakthrough technologies trigger another wave of replacements.

ELECTRICITY-INTENSIVE INDUSTRIES

ST +/–	MT +/––	LT +/––

In general, electricity-intensive industries will be hurt by the rising electricity costs that result from efforts to curb CO_2 emissions. These industries may have difficulty passing higher costs on to their customers and, at the very least, will have to adapt their capacity-expansion strategies to reflect the higher price of electricity once CO_2 emissions are constrained. Electricity-intensive industries (such as polysilicon producers) that supply equipment needed to reduce CO_2 emissions will likely find that the benefit of a new market opportunity partly or more than offsets the margin pressure from higher input prices.

Aluminum producers will be hurt in the short, medium and long term by rising electricity costs because aluminum smelting is among the most electricity-intensive industrial processes. Consequently, global production will continue to migrate to regions with access to relatively inexpensive cheap electricity, often from hydroelectric and geothermal plants. Aluminum production will, in effect, become a way for these regions to export their cheap power. Partly offsetting these pressures, demand for aluminum will increase in the medium to long term as the transportation sector seeks to incorporate more lightweight materials in order to increase fuel economy and reduce carbon emissions.

Cement manufacturers will also be hurt in the near term by more stringent environmental regulation because they are prolific emitters of CO_2 and other pollutants. The CO_2 emissions come, in part, from burning fossil fuels to heat a kiln. More importantly, it comes from heating calcium carbonate ($CaCO_3$) in the kiln to create calcium oxide (CaO). CO_2, which is created as a by-product, is released into the atmosphere. In the short term, as emission controls tighten, cement manufacturers could be required to retrofit existing plants with pollution controls or to reduce utilization levels. If emissions controls tighten in Europe and the US before they tighten in North Africa and Latin America, cement production (and associated emissions) may shift to the less-regulated areas.

In the medium to long term, however, cement industry fundamentals look strong. Cement is a relatively scarce building material, particularly in the US, so prices should rise if tighter environmental regulations place constraints on production. Over the past 25 years, cement prices in the US have risen steadily, virtually without regard to interest rates. Furthermore, if climate change leads to more violent hurricanes and typhoons, cement should edge out competing building materials because of its rigidity.

For the **chemical industry**, emissions controls on greenhouse gases create both risks and opportunities. The industry consumes about 5% of all crude oil and 10% of all natural gas produced globally. In the short term, the industry will have to adopt new low-emissions technologies. But chemical companies that specialize in industrial gases should benefit in the short, medium and long term. Both oxy-fuel and current IGCC technologies require pure oxygen to enable carbon capture.

Companies such as Air Products, Praxair, Linde and Air Liquide, which together command 70% of the $58 billion global industrial gas market, stand to gain substantially from the segment's growth. We estimate that just supplying oxygen to the IGCC-power plants proposed today would require $750 million worth of equipment in 2008 and $2 billion in 2009 from these companies. The market opportunity should expand substantially as clean-coal technologies are pursued more broadly. We expect related spending to exceed $5 billion by 2015 and $25 billion by 2020. Of course, separating oxygen from ambient air using currently available technologies is itself energy-intensive. Process changes and technology breakthroughs that reduce this energy penalty could be game changing for industrial-gas companies.

Polysilicon manufacturing is another electricity-intensive industry that stands to profit from CO_2 regulations in the near term, given the public policy support for solar generation. Contract and spot prices for polysilicon, the crucial raw material in most solar modules, have risen significantly as demand has outstripped supply growth. As a result, the small group of suppliers is enjoying abnormally high profits. These high profits, however, are attracting new entrants to the field, which will eventually lower returns. It takes only two or three years to build new polysilicon-manufacturing facilities, so we expect supply and demand to come into balance relatively soon. While sales growth of more than 30% will persist in the short term, we expect profits for polysilicon manufacturers to normalize as capacity is built to meet demand.

ELECTRIC UTILITIES

ST ++/−−	MT +++/−−	LT ++

Integrated utilities with electric generation, transmission and distribution assets dominate power generation globally. In the near term, integrated utilities are likely to diversify their power-generation assets to provide maximum flexibility ahead of stricter emissions requirements. Generally speaking, the greater a utility's CO_2 emissions per megawatt-hour of electricity production, the greater the potential regulatory risk in a carbon-constrained future.

In the US and Europe, government mandates for renewable energy are forcing utilities to either invest in wind and solar projects or to buy renewable power from third-party producers. Utilities with nuclear assets may benefit in the near to medium term as the marginal cost of fossil-fuel-based power rises to account for its carbon emissions.

In the medium to long term, CO_2 limits pose significant infrastructure and business-model challenges for the utility industry; they also offer opportunities. In addition to capital spending on maintenance and increased capacity, we estimate that by 2020 an incremental $225 billion per year will be spent globally to reduce CO_2 emissions from electric generation. For the most part, we expect utilities to be able to recover these expenditures through higher prices.

+++	Highly Positive	−	Negative
++	Very Positive	−−	Very Negative
+	Positive	−−−	Highly Negative

In the near term, **regulated utilities** that operate under a return on equity, or tariff-driven, business model are likely to see regulators recognize that improving electrical efficiency is the lowest-cost option for reducing CO_2 emissions. In some local or regional markets, industry incentives may change from maximizing production to maximizing energy efficiency. A "smart" electric grid, capable of two-way communications and dynamic matching of supply and demand, will make this new business possible.

In the medium to long term, regulators are likely to require reduced emissions and allow rate hikes that enable utilities to recover fairly quickly capital expenditures for building clean generating plants, particularly clean coal and nuclear plants. Under such conditions, these entities should enjoy significant top-line growth, coupled with fairly steady returns. Higher electricity prices would also foster the development of new business models for demand-side management for utilities on a much broader scale.

Pure-play, **unregulated merchant generators**—firms that make electricity and sell it on the open market—make up a very small portion of power generation globally. Most of these entities operate in parts of the US, UK, continental Europe and Argentina. Merchant power producers have to be judicious in allocating capital. Since they cannot bill the substantial capital cost for nuclear or clean coal-power plants to "captive" rate payers, they must cover their expenses and make a profit on open-market power sales. Hence, merchant power suppliers are more likely to focus on opportunities in tight power markets where natural gas sets the marginal price and there are high barriers to entry for new base-load generation. The largely deregulated power markets in the northeast of the US are sterling examples.

The two key variables for merchant producers are the type of fuel that they use and the type of fuel that sets the marginal price of electricity in the markets in which they compete. In the short to medium term, reserve margins are likely to tighten in part because of limited investment prior to clarification of impending regulations. As a result, less efficient or high-cost generating assets will increasingly set power prices. Unregulated players should fare well, particularly in forward-capacity markets[122] where rents and substantial returns can be earned for having generation assets or demand-response plans in place to satisfy peak-load requirements. Traditional coal-power suppliers will likely wage an uphill battle to earn adequate returns if they are not granted generous emissions allowances. In the long run, however, nuclear operators will be advantaged by having the lowest marginal cost and no exposure to CO_2 regulations.

In the medium to long term, merchant producers are likely to launch capital-intensive projects, such as new nuclear or clean coal plants, only if they have reasonable certainty about costs or pricing. Cost certainty may be gained by the equipment vendor bearing the risk of cost escalations and project delays. Alternatively, merchant producers may try to manage the costs themselves and enter into an agreement to sell the power at a fixed price in the future.

In the medium term, integrated utilities with merchant subsidiaries in competitive markets may see tensions arise between their merchant and regulated affiliates over passing through market-based prices and allocating capital. Such tensions may lead some of these firms to spin off their merchant subsidiaries.

As CO_2 regulation intensifies, the allocation of emissions allowances will have a material impact on profitability or many firms. Investors will need to carefully monitor such allowances and their financial impact on a company-by-company basis.

ENERGY-EFFICIENCY ENHANCING TECHNOLOGIES

ST ++	MT +++	LT +++

The majority of the world's energy is used to satisfy electricity and transportation needs. There is significant opportunity to enhance the end-use efficiency of a wide variety of electric applications used in homes, office buildings and factories, as well as motor vehicles. Rising energy prices and more stringent efficiency regulations will likely spur demand for energy-efficient products in the short, medium and long term.

Semiconductor and Technology Firms

The primary beneficiaries of this shift will be semiconductor and technology companies, since their components are critical for variable-speed drives, hybrid electric vehicles, advanced lighting, power management and other technologies that enhance the efficiency of electronic devices. Semiconductor manufacturers also stand to benefit from the increased deployment of solar panels, wind

122 Forward-capacity markets are designed to meet a service area's forecasted electricity demand and reserve requirements. Both generation and demand-response resources participate in the market and are paid to have capacity or demand-response mechanisms in place to balance the market when called on by the independent system operators.

turbines and HVDC lines. Other winners will include makers of efficient motors, permanent magnets and advanced lighting components and fixtures.

Variable-speed drives enable motors to vary power consumption with load conditions, start and stop softly and shut down when not needed. They also allow the elimination of inefficient mechanical controls. Variable-speed drives can thus boost the efficiency of a typical motor system by 25 percentage points, but they increase the up-front cost versus the cost of a standard motor system. The main components of a variable-speed drive are power semiconductors, such as rectifiers, converters and inverters, which account for the bulk of the dollar content for the drive, and logic/integrated circuits, such as sensors and microcontrollers. Manufacturers of both types of components should benefit from the increased adoption of variable-speed drives. Since the logic market is now several times larger than the power-semiconductor market, the variable-speed drive opportunity will be more beneficial for power-semiconductor providers.

The global market for variable-speed drives stood at $7 billion in 2005. Companies participating in the market, such as International Rectifier, Infineon and IXYS, have suggested that their associated product lines were growing significantly. We expect the market to grow by at least 15% a year through 2015.

Today, the automotive-electronics market is roughly $65 billion and growing at over 15% per year. Strong market growth should continue and may even accelerate. The number of sensors, electronic control units/microcontrollers, telecommunication and navigation devices will continue to increase.

With revenues of about $20 billion, the automotive semiconductor market accounts for a large percentage of the automotive-electronics market but only about 10% of overall semiconductor sales. We expect the semiconductor content per conventional vehicle to grow by more than 60% from about $275 per vehicle today to at least $450 per vehicle over the next five years, driven by demand for enhanced safety systems, entertainment modules, fuel efficiency and emissions control.[123]

Hybridization takes the electric content of the automobile to a new level: Nearly 50% of the cost of a full hybrid vehicle is for electric components, versus 15% in the case of a conventional model. This is largely due to the need for a host of new components, such as advanced batteries and electric motors. These components should provide significant growth opportunities to both auto parts suppliers (discussed on page 96) and to semiconductor companies. The dollar content of the semiconductors in a hybrid vehicle is 50%–200% greater than in a conventional vehicle. The big-ticket semiconductor items in the hybrids mostly perform power-management functions; they include electronic control units, battery-management systems, converters and inverters.

Among these, high-voltage inverters offer particularly high value-added. Using a semiconductor-switching device known as an insulated-gate bipolar transistor (IGBT), an inverter converts direct current from the hybrid's batteries to alternating current to drive the electric motor that powers the wheels. The inverter also converts alternating current to direct current when it takes power from the generator to recharge the batteries. We expect the automotive semiconductor market's growth to accelerate, largely because of increased adoption of hybrid vehicles.

Semiconductor and technology firms are also likely to see growth from increased wind and solar installations. Inverters are critical to solar and wind power because of their robust conduction and switching capabilities.[124] Therefore, the growth of these renewable-energy sources should also benefit semiconductor companies. Solar inverters convert the direct electric current that solar panels produce into alternating current, so that it can be loaded into the grid or used to run home appliances or other applications. The cost of a solar inverter runs from as low as $40 for a four-kilowatt residential system to over $20,000 for a five-megawatt system.

For wind power, inverters are crucial for stabilizing the wide variation in electric amplitude and frequency that result from changing wind conditions. Wind power is first converted from alternating current to direct current and then back to alternating current at the desired

+++	Highly Positive	–	Negative
++	Very Positive	––	Very Negative
+	Positive	–––	Highly Negative

[123] CLSA, Lehman Brothers and AllianceBernstein

[124] Richard Kaiser, Vadim Zlotnikov and Denis Smirnov, LTD, "Technology Sector Strategy: Global Warming Challenges, Information Technology Solutions" (Sanford Bernstein & Co., October 2007)

amplitude and frequency. Each wind turbine deployed requires this power converter/inverter, which represents about 2% of the cost of a typical two-megawatt turbine, or about $80,000. Wind turbines also usually require transformers, which are power semiconductors that step up and step down voltage as needed across the system, from the relatively low-voltage turbine to the high-voltage grid. Additionally, wind turbines have relatively complex control and positioning systems to adjust the pitch and angle of rotor blades as wind speed and direction change. This helps to optimize power generation under varying wind conditions. These systems require sensors, microcontrollers and software technology.

Growth in energy-efficient advanced lighting systems should benefit semiconductor and technology firms with expertise in the design and manufacture of more efficient circuits, power supplies and voltage regulators and with competencies in diodes and other components for advanced lighting.

Motor, Magnets and Lighting

Motor manufacturers, magnet providers and lighting companies should also benefit from demand for greater energy efficiency as carbon-emissions controls drive up electricity prices.

We estimate that global sales of electric **motors** reached roughly $30 billion in 2005; only $5 billion of the total was for high-efficiency motors. These motors typically raise motor efficiency by about 3–5 percentage points at an up-front cost premium of 20% to the cost of a standard motor. Manufacturers that cannot successfully make the transition from standard to efficient motors will likely lose market share and profitability. Companies participating in the market, such as Baldor Electric, have reported significant growth in efficient-motor sales over the past few years. This trend is likely to continue. We expect the future growth rate of the efficient-motor market from now until 2015 to be at least 15% a year.

Magnets have long been essential to many electric motors, although today's alternating-current motors typically induce a magnetic field electrically rather than by using magnets. Magnets are becoming more important again, precisely because they do not require the use of electricity. Efficient motors available today for equipment ranging from home appliances to hybrid vehicles use permanent magnets, made from rare earth minerals, principally neodymium. The cost of neodymium, which comes primarily from Inner Mongolia in China, soared from $4 per kilogram in 2002 to $33 in the third quarter of 2007. The nickel metal hydride batteries in hybrid vehicles today use 10–30 kilograms of various rare earth elements.[125] We expect providers of rare earth minerals, as well as makers of permanent magnets, such as Hitachi Metals, to benefit in the near, medium and long term as efficient motors increasingly take share in industrial, commercial and residential sectors, and as hybrid vehicles come to dominate new car sales.

The **lighting** market generates over $100 billion in sales globally. Fixtures and lamps constitute nearly 80% of the market; lightbulbs make up the rest. The majority of lightbulbs sold are incandescent or standard fluorescent bulbs, which General Electric, Philips Electronics and Siemens dominate. They enjoy very high margins in this traditional business because the technologies are mature and the assets are fully depreciated. We expect profitability for traditional bulbs to decline as efficiency standards become more pervasive. Australia has decided to ban incandescent lightbulbs beginning in 2012. Emerging new technologies will also erode the sales, and ultimately the profitability, of traditional lighting products.

Some traditional lighting companies have embraced the compact fluorescent lightbulb (CFL), which is more efficient than the incandescent bulb and offers higher-quality illumination than the standard fluorescent bulb. It usually works in the same fixtures as incandescent bulbs. We expect compact fluorescent lightbulbs to take share in the short term. Over the medium to longer term, however, we expect light-emitting diodes (LEDs) to be the winning technology. LEDs offer the potential for still-higher efficiency and quality, as well as versatility and long life. Also, they do not use mercury, which is subject to hazardous-waste regulations in some parts of the world. Today, LEDs are believed to represent just 1% of the total lighting market.

Philips and Siemens have begun investing in LEDs and other lighting technologies. Philips has publicly stated its intention to phase out incandescent bulbs by 2016. It has made several acquisitions in LED lighting solutions in order to become a vertically integrated provider of LEDs. It is also seeking to influence the establishment of production standards for LEDs, which do not exist today. Given that LED bulbs are long-lived and require new fixtures, the largest profit potential with regard to this technology may be in fixtures and installation.

[125] Walt Benecki, SPS Technologies and Gary Billingsley, Great Western Minerals Group, http://www.planetark.com

ENGINEERING AND CONSTRUCTION

ST +++	MT +++/–	LT +++

Engineering and construction (E&C) firms should benefit steadily from regulation of CO_2 emissions and rising cost trends, as new infrastructure projects drive a prolonged investment cycle. E&C firms typically are more leveraged to the capital-spending cycle for power generation than other industry groups. Operating margins that quadruple from 2% at the trough to 8% at the peak are not uncommon for some of these firms. Barriers to entry are fairly high, given the long-term relationships between industrial customers and contractors and the shortage of skilled-trade workers. E&C firms that focus on E&C work for nuclear plants or clean-coal plants will benefit in the medium and long term as opportunities proliferate and order backlogs build. Over the medium to long term, the complexity of these projects and the possibility of cost overruns, overbuilds and design fixes may reduce the upside if contracts are not written carefully. Unforeseen circumstances can also create delays that have a material impact on earnings, creating unevenness in quarterly results that can be difficult to forecast.

TRANSPORTATION

ST ++/––	MT +++/–––	LT +++/–––

Within the transportation sector, manufacturers of automobiles, trucks and buses across the globe will increasingly face tougher fuel-economy standards and stricter emissions-control requirements on CO_2, as well as other pollutants, such as nitrogen oxides and particulates. In the near term, several technologies and fuels may help them to comply with new regulations. These include advanced gasoline engines; smaller, lighter-weight cars; hybrid power trains; and biofuels and diesel. Firms with such offerings are likely to maintain or increase their market shares.

Over the medium to long term, regulatory hurdles will become more challenging. Hybrid vehicles are likely to become the automotive standard, since their power train can be used with multiple fuels and technologies to offer a high-quality driving experience with significantly lower fossil-fuel intake and lower CO_2 emissions than the alternatives. While hybrid technology is expensive today, the costs are likely to continue to decline by about 10% per year with economies of scale and learning-curve effects, making plug-in hybrids viable for the mass market in several years. The shift to hybrids will create large new market opportunities for suppliers with core competencies in electronic components and lithium batteries. By contrast, cost-competitive hydrogen fuel-cell technology and the hydrogen infrastructure necessary to make hydrogen fuel-cell vehicles viable are unlikely to develop before 2030.

Automakers

A wide discrepancy in hybrid expertise exists among the major automobile manufacturers. Toyota Motor clearly leads the market today, capturing the majority of all hybrid vehicles sold globally. In the near to medium term, Toyota (and its suppliers) should benefit the most from the transition to hybrid vehicles, given its core competencies in advanced electronics, other automotive technologies and manufacturing. Toyota maintains robust and efficient supplier networks.

Honda is currently a distant second to Toyota in the hybrid market, but it stands to benefit in the near to medium term from its portfolio of small cars and advanced engine technologies. Honda has the highest average fuel efficiency among the automakers. Other automakers have been slower to make the transition from large, fuel-inefficient pickups and sport utility vehicles (GM and Ford Motor) or smaller, dirtier diesel cars (Renault and Peugeot) to cleaner, more efficient vehicles. Such automakers are now aggressively building their capability in this area.

We expect that, ultimately, all automakers will have to produce hybrids to survive and prosper. Automakers without hybrid offerings will likely lose market share and profitability. Thus, companies with limited hybrid expertise will have to invest in developing the technology themselves, enter into partnerships or pay relatively large licensing fees to use other firms' technology.

General Motors, Daimler and BMW formed a research and development partnership in late 2005 to commercialize full hybrids, with the first offerings in late 2007. GM is also pursuing plug-in hybrids independently, in a bid to outflank Toyota for the leadership position in next-generation hybrid technology. In 2010, GM's Chevy Volt may become the first commercially available, mass-produced plug-in hybrid. As of now, it is unclear if GM will match the fuel savings, performance, cost and quality of Toyota's hybrid offerings.

+++	Highly Positive	–	Negative
++	Very Positive	––	Very Negative
+	Positive	–––	Highly Negative

Four European manufacturers—Audi, Peugeot, Porsche and Volkswagen—have also elected to cooperate on hybrid systems. They appear to be focused on developing a supplier network around Continental AG that can deliver hybrids on a turnkey basis. These efforts will take time; the first vehicles from this collaboration may not reach showrooms until 2009.

At this point, Ford, Fuji Heavy Industries and Nissan Motor are choosing to pay licensing fees to Toyota.

Auto Parts Suppliers

Most innovation in the automotive sector in recent years has been in electronic components that make cars more sophisticated and efficient. Electronic components have moved from simple ignition, lighting and open/close functions (such as power locks and windows) to advanced sensors and parts regulating complex engine and emissions controls. A slew of safety and entertainment features have also emerged.

As a result, the total cost of electronic components has jumped to 15% of the bill of goods for today's conventional car from 5% in 1977. In full hybrids, the electronic bill of goods is much higher, at about 50%. While this trend benefits suppliers of a variety of electronic systems, the companies that stand to benefit the most are those that specialize in hybrid-specific electronic components, such as advanced batteries, electric motors and generators, electronic control units/microcontrollers, sensors, electronic and regenerative braking systems, electronic steering and transmission systems.

The single biggest growth opportunity lies in **advanced batteries and battery-management systems**. Today, annual revenues for automotive batteries for light-duty vehicles, almost all them lead acid batteries, are about $9 billion, including sales to original equipment manufacturers (OEMs) and aftermarket sales. We estimate that total annual revenues could grow to at least $150 billion in OEM sales alone by 2030. This estimate reflects our projection that unit sales of light-duty hybrid vehicles will be 74 million in 2030, 85% of total cars sold. If the average cost of the advanced hybrid battery is $2,000 per vehicle to the OEM, the automotive battery market would reach nearly $150 billion from OEM purchases. Aftermarket sales would boost the market significantly higher. If the price is $3,000 per vehicle, the OEM slice of the automotive battery market would reach nearly $225 billion. Hybridization of trucks and buses would make total revenues for the battery market even larger.

Batteries are a crucial, big-ticket item in hybrids, representing upward of 50% of the added cost of goods sold. Hence, advanced-battery manufacturers have become new entrants into the auto space. Those with robust lithium technology are particularly well positioned over the medium to long term. Automakers require both robust battery chemistries and assurances of product reliability and supplier dependability. Thus, Tier 1 automotive suppliers with reputable manufacturing operations are increasingly partnering with battery producers to market their products jointly to the automakers. Examples of such relationships are the joint ventures between Matsushita Electric and Toyota and between Saft and Johnson Controls.

Suppliers of **other electronic parts** outside of the power train and battery system are also likely to benefit considerably from hybrid market growth, since hybrids will accelerate the trend to increased electronic content per vehicle. The investment implications for technology firms of the electrification of the automobile are discussed under the heading "Energy-Efficiency Enhancing Technologies," on page 92.

In the medium to long term, suppliers of conventional mechanical systems such as brakes, steering and transmissions are likely to see their unit sales and profits decline as many of these systems are downscaled or replaced by new electronic systems made possible by the higher voltages that hybrid vehicles can support.

Suppliers of **advanced technologies for conventional vehicles** that lead to higher efficiencies without performance penalties are also likely to do well in the near term. Hybridization will take some time to unfold, and the automakers that are behind in the development of hybrid technologies are likely to try to retain market share by offering considerable improvements to conventional vehicles. In the medium to long term, these suppliers will do well only if their technologies can be successfully integrated into hybrid platforms. Examples of technologies that can be applied to conventional as well as hybrid vehicles include variable-valve timing and cylinder-deactivation devices, common rail diesel systems, flex-fuel engines and carbon-fiber composites. ■

Appendix A:

Our Power-Generation Model in Detail

Our forecast for power-generation infrastructure through 2030 has been an integral part of this research project. We do not, of course, believe that the global power fleet will develop exactly as we outline. Nonetheless, developing this detailed scenario analysis allowed us to estimate potential expenditures on power infrastructure through 2030 and to demonstrate how this build-out would affect emissions and atmospheric concentrations of CO_2 leading up to 2030 and beyond. If our primary assumptions prove to be correct, we expect the drivers of growth and the shape of the coming capital-expenditure boom to be roughly along the lines of our forecast.

POWER-FLEET ASSUMPTIONS AND METHODOLOGY

We began with three primary assumptions:

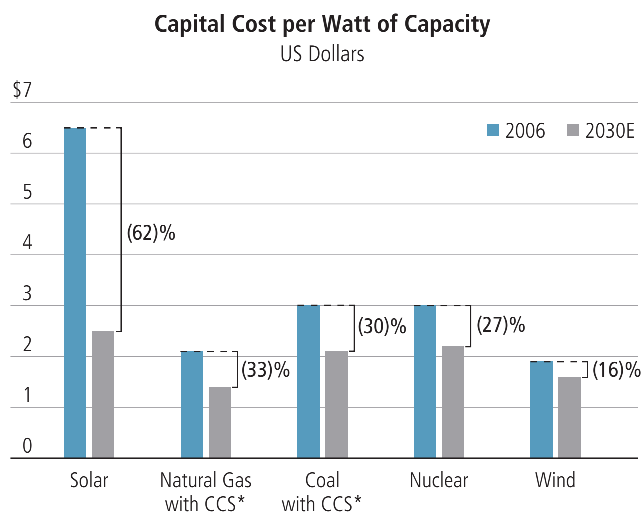
- Regulations to reduce CO_2 emissions will be adopted globally;
- Utility providers will seek least-cost methods of meeting demand; and
- Regulatory support for renewables will encourage expansion of wind and solar power.

We developed an array of more detailed assumptions from our primary assumptions to model a likely scenario for the development of the global power fleet. Among these more detailed assumptions were:

- **Electricity-demand projections** based on GDP growth levels included in the EIA's 2007 International Energy Outlook reference case, with usage levels based on regional analysts' expectations for efficiency gains. Where appropriate, we took into account incremental demand from plug-in vehicles and demand destruction due to the adoption of electrically efficient devices.
- **Significant capital cost declines for developing technologies.** We expect capital costs for wind, solar, clean coal, natural-gas and nuclear power to decline by 2030. We expect these costs to fall most for solar and least for wind power (*Display 86*).
- **Normalization of commodity prices.** We expect commodity prices to revert to more normal levels from their current elevated levels over the course of our forecast period.

Display 86

Costs Will Fall for Emerging Power Technologies



**Carbon capture and storage*
Costs in constant 2007 dollars for developed countries; does not factor in operating costs or utilization rates
Source: AllianceBernstein

We also assume that natural-gas prices will remain volatile and vary from $4 to $8 per million BTUs.

- **Stringent global carbon regulations.** We expect there to be a post-Kyoto global carbon agreement in place by 2012 and that it will not require emissions reductions from developing countries until 2020.

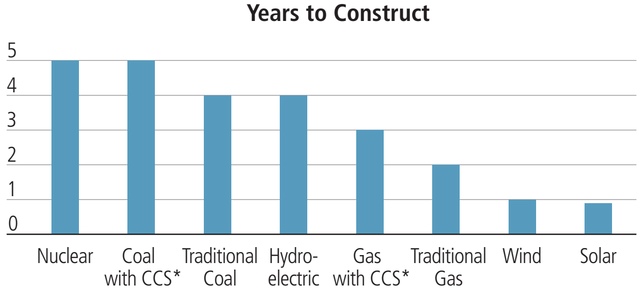
We also included a broad array of constraints in our model:

- **Time to build.** In developing our infrastructure build-out on a plant-by-plant basis, we took into account the time required to construct a physical plant (*Display 87*). We also included the time to receive permits.
- **New technology ramp period.** Many of the technologies we discuss in this report are still relatively immature. Although significant research-and-development efforts and funding are focused on their improvement, we do not project widespread deployment of these solutions until the second half of our forecast period.
- **Aging infrastructure.** Infrastructure retirement plays a significant role in determining incremental spending on power infrastructure. As such, we modeled retirement schedules for the existing nuclear, coal and natural-gas fleets. We assumed that some portion of these plants would remain economical to operate past their proposed retirement dates and would thus continue to run longer.
- **Regional differences.** In developing our model, we employed a bottom-up approach, dividing the world into six discrete regions: the US, developed Europe, developed Asia (both defined by membership in the OECD), China, India and everything else, which we call "Rest of World." This approach allowed us to account for regional differences in resource availability, construction costs, current infrastructure and regulations.

The first five years of our model forecasts are informed by projects already in the planning, development, procurement or construction stages, which can take several years. Data from utilities' publicly announced plans as well as extensive interviews with industry experts and consultants have also informed our near-term projections, although we do not expect every project planned to come to fruition.

Display 87

Power Plants Generally Take a Long Time to Build



**Carbon capture and storage*
Source: AllianceBernstein

In later years, we populated the model in accordance with the assumptions, constraints and electricity-demand forecast described. We simulated the decision-making processes of power producers in each region, sometimes on a plant-by-plant basis.

Our Business-as-Usual Model

To form a business-as-usual scenario (or base case) against which to compare our forecast, we followed the same methodology but eliminated all assumptions regarding post-Kyoto CO_2 regulations. In large part, this scenario was based on the EIA's forecast of power capacity.

Throughout the forecast period, we adjusted the utilization rates of various fuel types to meet electricity demand in a least-cost manner, as any power-plant operator would. We took into account the limitations of the various fuel types. For example, wind turbines provide 20%–50% of their rated capacity, depending upon the wind quality of their location, while utilization rates for nuclear plants depend primarily on the percentage of time that the plants are off-line for maintenance. ■

MODELING THE US POWER BUILD

The power fleet in the United States now has about 1,100 gigawatts of generating capacity. It includes an aging coal and nuclear fleet, thousands of small natural-gas plants pressed into service only to meet peak demand, and a small renewable infrastructure composed largely of hydroelectric plants. Coal and nuclear energy provide base-load power and operate at high utilization rates (64% and 91%, respectively, on average). Together, coal and nuclear plants provided 2.7 trillion of the 4 trillion kilowatt-hours, or almost 70% of the total electricity consumed in the US in 2006 (*Display 88*).

Our Electricity-Demand Forecast for the US

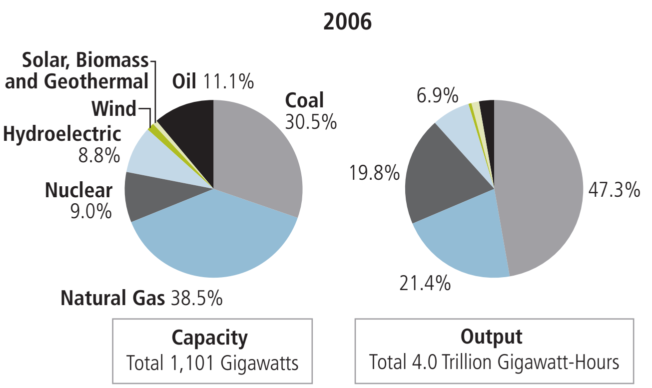
Efficiency increases and structural changes have allowed US economic growth to partly decouple from electricity consumption. In 1980, the US generated $2.10 of economic product for every kilowatt-hour of electricity used; in 1990, the country produced $2.20[126] for every kilowatt-hour. By 2006, output per kilowatt-hour had risen to $2.90. We expect continued improvements in electric efficiency that will allow this trend to accelerate. If the US economy grows about 3% per year on average, it will generate over $22 trillion of GDP a year by 2030. In that case, we project that electricity demand will be just over 4.8 trillion kilowatt-hours, implying that for every kilowatt-hour used, the US will produce $4.70 in economic product.

The Build in the US

Today, the US has a shortage of electric capacity. Political obstacles to building coal plants have led many power producers to build natural-gas plants to meet short-term demand while they seek approval for coal-generating

Display 88

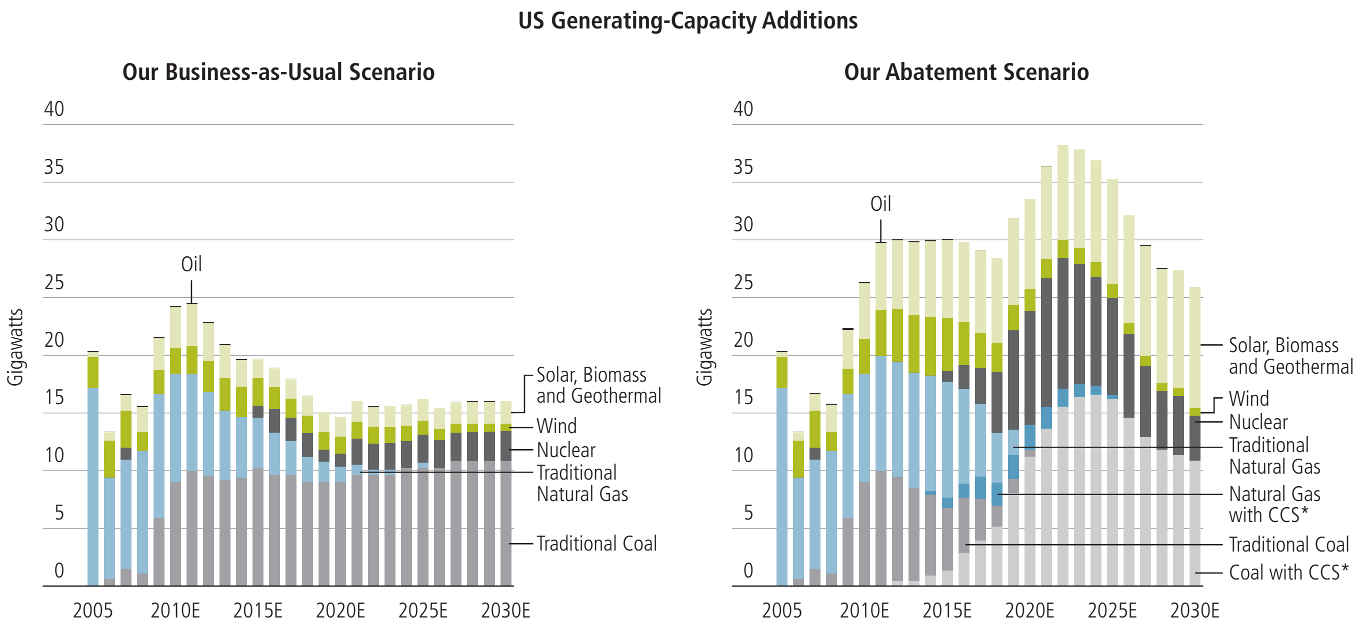
Coal and Natural Gas Dominate US Power Fleet



Source: EIA, IEA and AllianceBernstein

Display 89

Climate-Change Concerns Will Transform New Build in US



* *Carbon capture and storage*
Source: EIA, IEA and AllianceBernstein

[126] All GDP numbers are inflation-adjusted to year 2000 dollars comparable on a purchasing-power-parity basis.

plants to go into operation by the end of the decade. After a long hiatus, many US utilities are also considering nuclear power: Only two of the 104 nuclear reactors operating in the US today were built in the past 15 years. Nuclear-power plants now under review will not come online until 2015 or beyond. Natural-gas plants are attractive because they are quicker to build, require about half as much capital as a new coal facility and are politically palatable.

Coal power is the most economic alternative over the life of the plant, especially given the abundance of coal in the US. Thus, in a world without carbon constraints, power producers would likely build natural-gas facilities to cover the impending supply shortfall, while building pulverized-coal and some nuclear capacity to cover the country's longer-term base-load needs (*Display 89, left, previous page*).

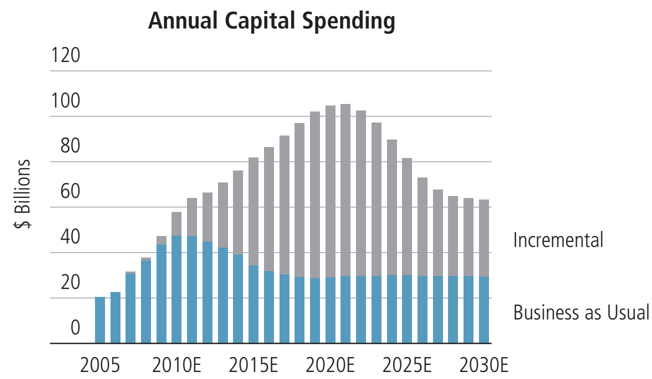
With CO_2-emissions regulations in place, however, a traditional coal-power plant may soon be rendered uneconomical. Thus, the timing and stringency of the regulations will be crucial in determining the facilities built from 2008 to 2012. We have assumed, for the sake of simplicity, that after 2012, stringent regulations will make it uneconomical for a utility to build a new facility that is not carbon-capture-ready.

It is significantly more expensive to build a traditional coal plant and later retrofit it for carbon capture than to build new carbon-capture-ready facilities. Thus, we expect that by 2015 (or 2018, at the latest), the cost of CO_2 emissions will be sufficiently high to provide utilities an economic incentive to begin to use low or no CO_2-emissions power for base-load supply on a meaningful scale. During the same period and into the early 2020s, many owners of coal-power plants are likely to find that the new cost of CO_2-emissions abatement has made some of their existing facilities uneconomic. These owners will either retrofit or shut down many of their legacy coal plants. But retrofitting reduces plant capacity, and accelerating retirements will also reduce overall power-generation capacity. As a result, far more new capacity will have to be built each year to offset the capacity reduction from regulation-related retrofits and retirements. The pace of new plant builds will only normalize after most regulation-prompted retrofits and retirements have taken place (*Display 89, right, previous page*).

The building boom prompted by CO_2-emissions controls will require tremendous capital investment, much of it on clean-coal and nuclear capacity (*Display 90*). By 2020,

Display 90

Emissions Abatement Will Add Hugely to US Power Capex



In constant 2007 dollars
Source: EIA, IEA and AllianceBernstein

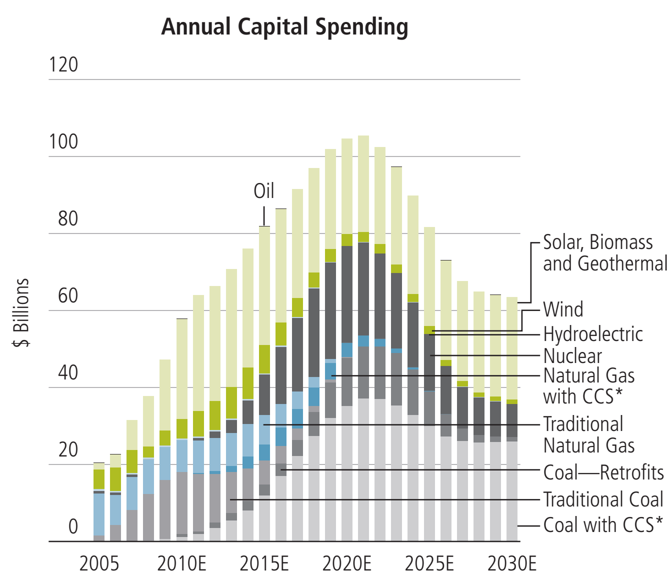
we project that carbon-abatement efforts will more than triple annual capital expenditures in the US, to above $100 billion annual compared with business-as-usual spending of less than $30 billion.

Investment Opportunity in the US

The incremental spending for each fuel type due to CO_2-emissions regulation provides a more in-depth picture of the change in spending (*Display 91*). Nuclear power is the most compelling short- to medium-term growth opportunity within the US. Many power producers already see investments in this CO_2-emissions–free technology for

Display 91

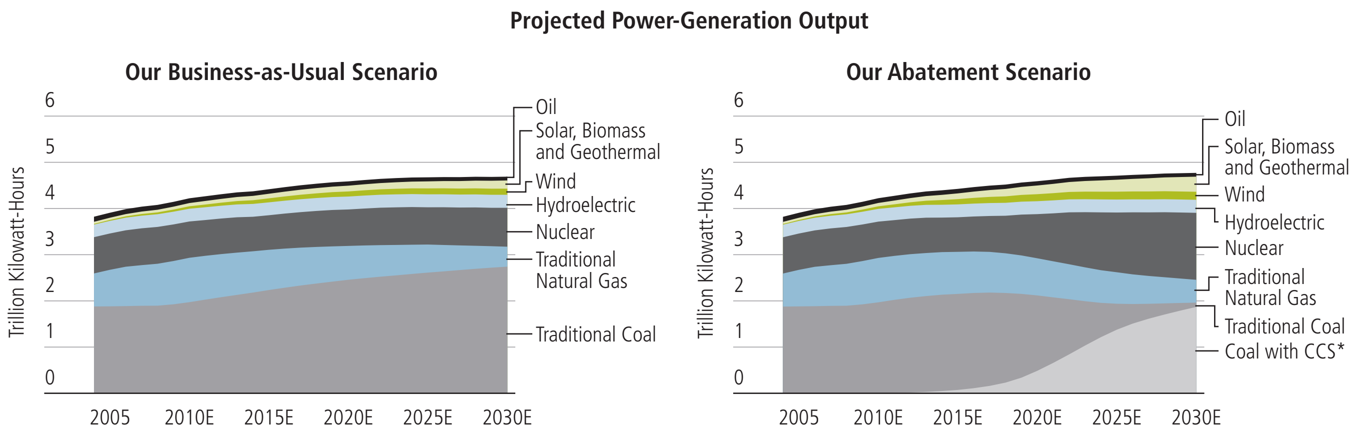
Clean Coal, Nuclear to Gain Most from Abatement in US



In constant 2007 dollars
**Carbon capture and storage*
Source: EIA, IEA and AllianceBernstein

Display 92

Abatement Will Shift US Power Output to Clean Coal and Nuclear



*_Carbon capture and storage_

Source: EIA, IEA and AllianceBernstein

base-load capacity as a way to protect themselves against impending emissions-related costs. Furthermore, the US federal government has established tax and other incentives to encourage utilities to build nuclear facilities. We project that by 2020, capital spending on nuclear power will reach $25 billion, versus $5 billion in our business-as-usual case.

Once a CO_2-emissions policy is set and the cost of carbon emissions becomes clear to operators, spending on clean coal plants will surge. Spending to retrofit existing facilities and build new carbon-capturing facilities will increase to $48 billion in 2020, more than triple the $15 billion spent on pulverized-coal plants in our business-as-usual case.

Growth in renewable energy will continue to be driven primarily by regulation, subsidies and renewable portfolio standards set by individual states or the federal government, rather than cost-competitiveness. Despite the tremendous wind resources in the US, adding a cost to carbon emissions would only marginally expand the number of economically compelling sites. Photovoltaic solar power is even less economically attractive today, but costs are falling rapidly. Whether solar power ever becomes truly cost-competitive remains to be seen.

Our 2030 Forecast for the US

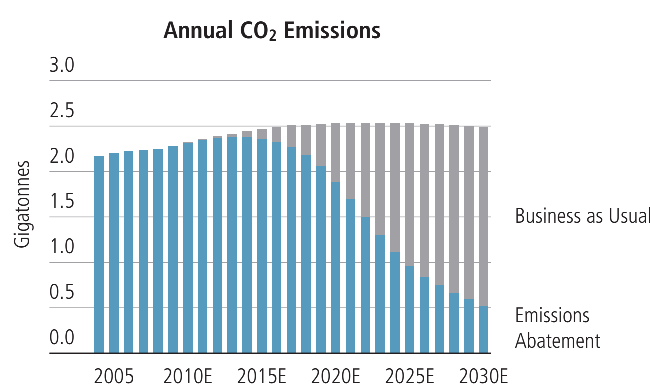
We expect the US power fleet to generate 4.8 trillion kilowatt-hours of electricity by 2030, with some 4.1 trillion kilowatt-hours coming from clean or near-clean power sources. Small, dirty coal plants will still provide a limited amount of electricity. Natural-gas plants will continue to provide some peak-load power.

Remarkably, the coal fleet's share of total US power output will fall from 47% in 2006 to 41% in 2030, despite the massive incremental spending. In our business-as-usual model, however, coal power would provide 59% of total electric output in 2030. In our emissions-abatement model, nuclear power would gain share at coal's expense, rising from 20% in 2006 to 30% in 2030 (_Display 92_).

We expect significant reductions in CO_2 emissions in the US. The fuel-mix shift projected in our scenario would reduce power-fleet CO_2 emissions to less than 25% of their 2006 level (_Display 93_). The incremental spending on power related to carbon-emissions abatement would be equal to about 0.6% of GDP in the late teens through the early 20s. But the money would be well spent: The US power fleet would be emitting 110 tonnes of CO_2 per million kilowatt-hours, compared with 560 today. ■

Display 93

Abatement Will Cause US Power-Related Emissions to Plunge



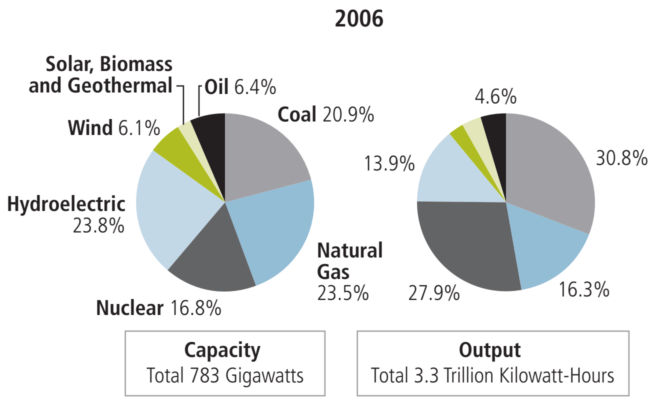
Source: EIA, IEA and AllianceBernstein

MODELING DEVELOPED EUROPE'S POWER BUILD

Developed Europe's existing 783 gigawatts of electrical capacity falls into four, roughly equal, parts: coal, nuclear, natural-gas and hydroelectric capacity (*Display 94*). In 2006, these four sources contributed 3 trillion of the 3.3 trillion kilowatt-hours of power produced. The utilization rate of the coal and nuclear fleets is significantly higher than that of natural-gas, hydroelectric power or other renewable sources. Despite significant subsidies for renewable infrastructure, wind and solar sources contributed less than 3% of total electricity produced in 2006.

Display 94

Nuclear and Renewable Energy Are Bigger in OECD Europe



Source: EIA, IEA and AllianceBernstein

Recent infrastructure investments have focused on developing natural gas as a base-load option, largely for environmental reasons. However, we expect this strategy to change as emissions-reduction targets become more restrictive and geopolitical tension over energy supplies persist.

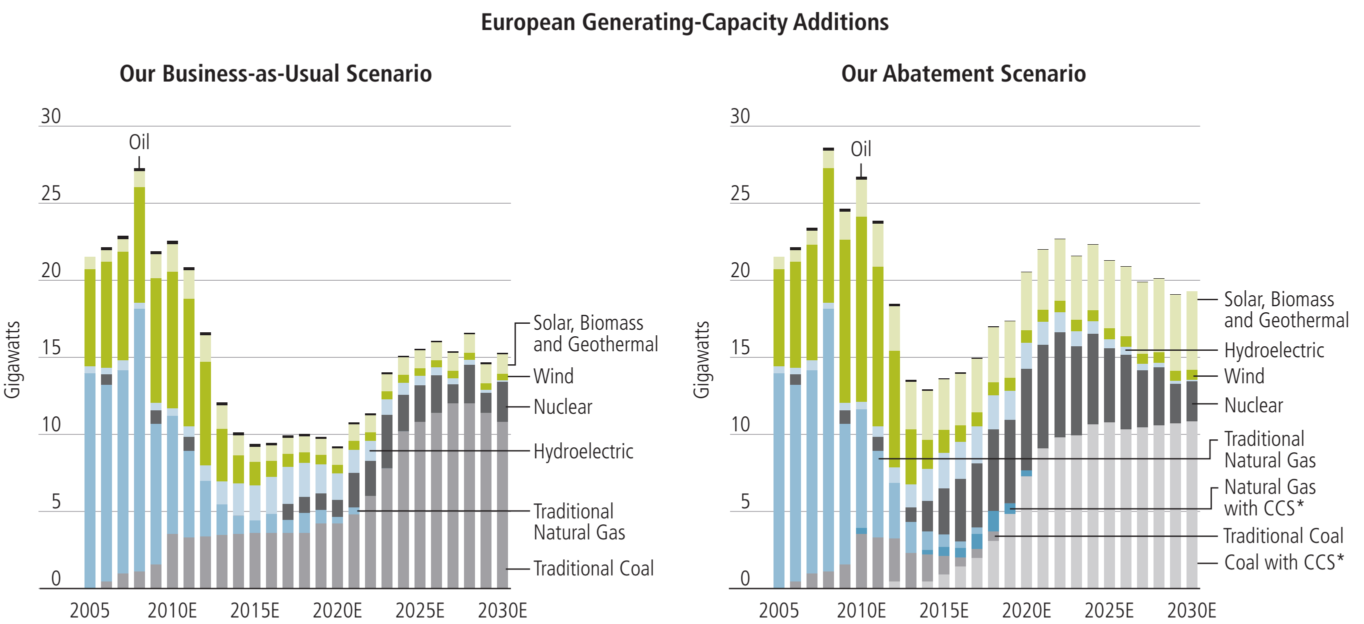
Our Electricity-Demand Forecast for Europe

Historically, more compact lifestyles and stricter efficiency-related regulations have enabled European countries to generate more GDP dollars per unit of electricity consumed than the United States. With recent gains in economic strength, the region is generating over US$3.50 in GDP per kilowatt-hour. Europe's higher electrical productivity reflects lower per-capita electricity consumption: It was roughly five megawatt-hours per person in 1990 and rose to just north of six by 2006, compared with 13 megawatt-hours of electricity per person in the US in the same year.

We expect the electrical intensity of developed Europe's economy to remain impressive and even improve as

Display 95

Climate-Change Concerns Will Transform New Build in Europe



**Carbon capture and storage*
Source: EIA, IEA and AllianceBernstein

electricity prices rise and more efficiency requirements are enacted. We project that by 2030, developed Europe will generate almost US$20 trillion of GDP (assuming compound annual growth of 2.2%), and its electricity demand will reach 3.8 trillion kilowatt-hours. For every kilowatt-hour used, we expect developed Europe to produce over $5 of output.

The Build in Europe

European power producers moved en masse to build natural-gas-power capacity in recent years, largely in response to Phase I of the EU Emissions Trading Scheme (ETS). Natural gas represents an attractive, low-risk power source in a mildly carbon-constrained regulatory environment. Capital costs are low, the plants are relatively easy to build and natural-gas plants emits half as much CO_2 per unit of produced power as coal. Given current projects under way, this trend will continue for the next few years.

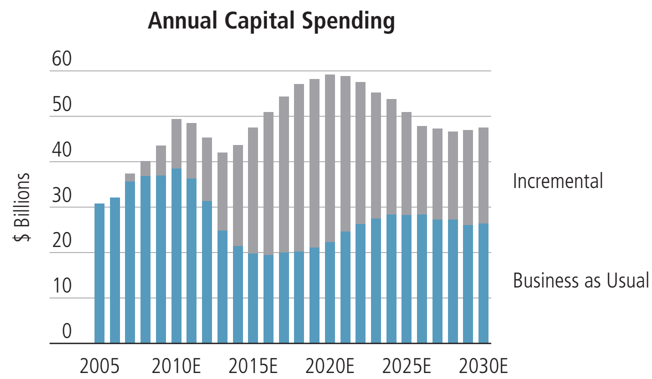
Under our business-as-usual scenario, if the Kyoto Protocol were to expire, power producers would seek to satisfy incremental base-load needs with traditional coal and nuclear power (*Display 95, left*). Price volatility and security concerns are likely to prevent natural gas from becoming a viable long-term solution to base-load power.

Europe has developed a wind-power fleet as a result of favorable government incentives. But EDF Energies Nouvelles, a French provider, has told us that most of the viable wind sites have already been optioned and will be fully developed by or before 2014. Additional carbon-emissions regulations and renewable-power requirements will likely improve the economic attractiveness of the best sites and may make some marginal wind fields attractive for development; we do not believe that they will dramatically expand the wind resources suitable for development in Europe.

Many power producers believe that a firm post-Kyoto agreement will be reached before 2012, so they are significantly curtailing their infrastructure build until the shape of the new rules becomes clear. The new regime is generally expected to include carbon-capture requirements for all newly built fossil-fuel power plants and significant financial incentives to pursue clean-energy solutions. The post-Kyoto building spree will include clean coal and nuclear power (*Display 95, right*). It will also include many plants built to offset the loss of capacity due to retrofits and early retirements. As carbon emissions become costly, natural-gas facilities will become less viable for base-load capacity. Thus, utilization rates of natural-gas facilities will fall, intensifying

Display 96

Abatement Will Add Hugely to European Power Capex



In constant 2007 dollars
Source: EIA, IEA and AllianceBernstein

the need for incremental capacity additions. By 2020, we expect developed Europe's yearly capacity additions in a carbon-constrained world to surpass 20 gigawatts, more than double those required in our business-as-usual scenario.

Yearly capital spending on power infrastructure, we project, will approach $60 billion by 2020, almost triple that forecast in our business-as-usual scenario (*Display 96*).

Investment Opportunity in Europe

We expect the European wind-power market to grow at a 17% compound annual rate over the next three years, creating a significant short-term investment opportunity. As the best remaining sites are fully developed, however, investment levels will quickly fall and will likely remain flat (*Display 97, next page*).

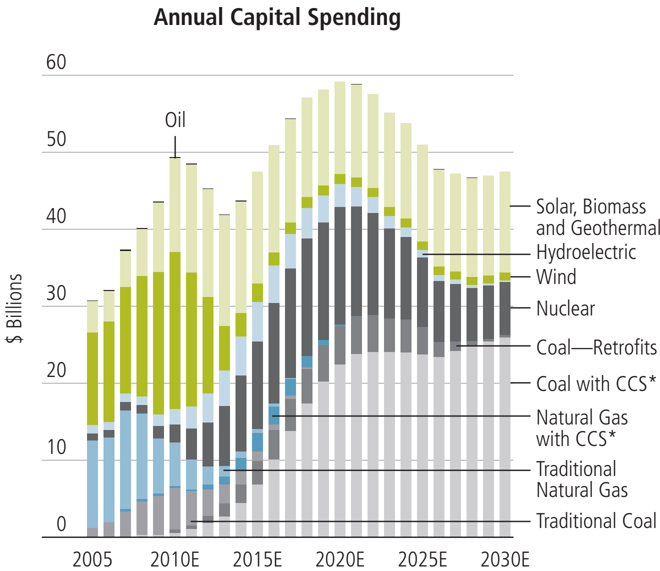
Spending on solar power is unlikely to increase significantly—despite high subsidies in Germany—until the technology can be installed at competitive costs. However, even if competitive costs are reached during our forecast period, Europe's lack of strong sun resources outside of the Mediterranean rim will severely curtail growth.

Nuclear power will likely grow quickly, because the tide of antinuclear sentiment that swept Europe after the Chernobyl disaster of 1986 is now turning. Spain, Germany and Sweden, which have plans to phase out nuclear power, will likely reverse course. France remains a strong proponent of nuclear power, and the UK has already announced plans to replace and expand its nuclear fleet as aging reactors are shut.

European power producers have already begun what we expect to be a significant nuclear-plant build. We expect investment in nuclear power to significantly increase even before a post-Kyoto accord is implemented. We project that nuclear capital expenditures in Europe will grow at a compound annual rate exceeding 20%, from $2 billion in 2010 to $15 billion prior to 2020.

Display 97

European Capex to Shift Away from Wind and Natural Gas



In constant 2007 dollars

**Carbon capture and storage*

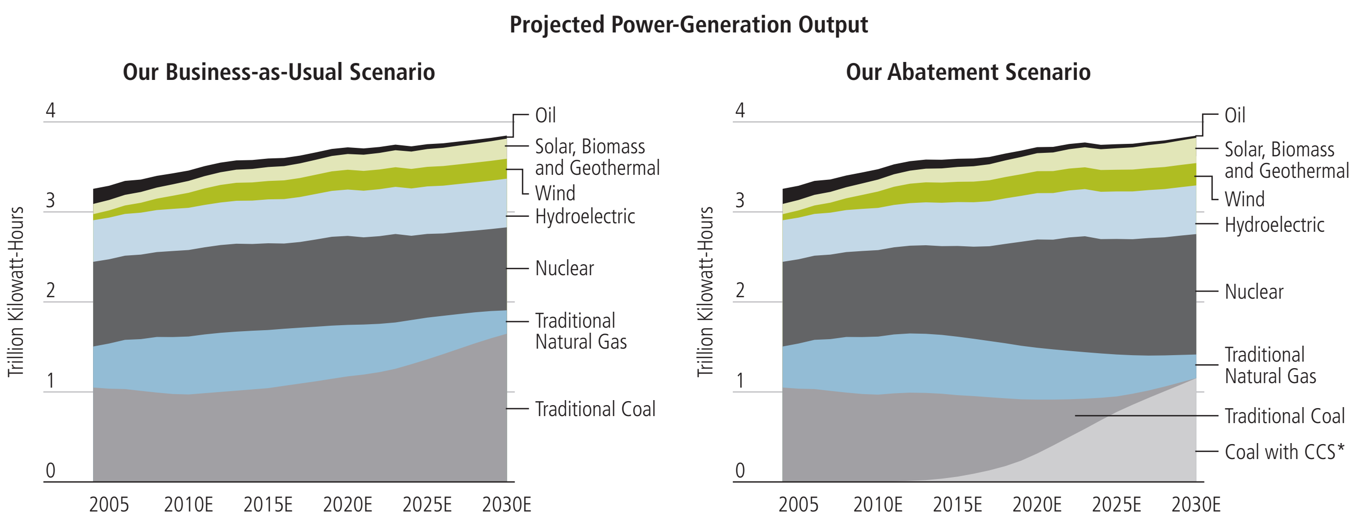
Source: EIA, IEA and AllianceBernstein

Power producers will be much less likely to invest in clean coal without regulatory certainty. Always cautious about new technologies, they are likely to be reluctant to adopt carbon-capture technologies without strong regulatory mandates, economic incentives or performance guarantees from vendors. Nonetheless, we expect the dam to break: In the next five to 10 years, either as a response to regulatory mandates or a high-enough long-term cost for CO_2 emissions,[127] a flood of capital will be deployed to build clean-coal plants in Europe.

Our modeling suggests that meaningful spending on clean coal will begin by 2015 and accelerate thereafter. This incremental spending, which includes retrofits of existing facilities and newly built carbon-capturing coal plants, will more than triple business-as-usual spending before 2020. After the vast majority of the existing coal fleet has been retrofitted or retired, spending growth will likely moderate, but utilities will continue to build carbon-capturing coal plants to provide relatively cheap and reliable base-load power.

Display 98

Abatement Will Shift Output in Europe to Clean Coal and Nuclear



**Carbon capture and storage*

Source: EIA, IEA and AllianceBernstein

[127] Our research suggests that at US$50 per tonne, CO_2 emissions would be sufficiently costly to inspire switching to coal power with carbon capture and storage, given today's technology. The 2008 vintage EU ETS future currently trades at US$32 per tonne.

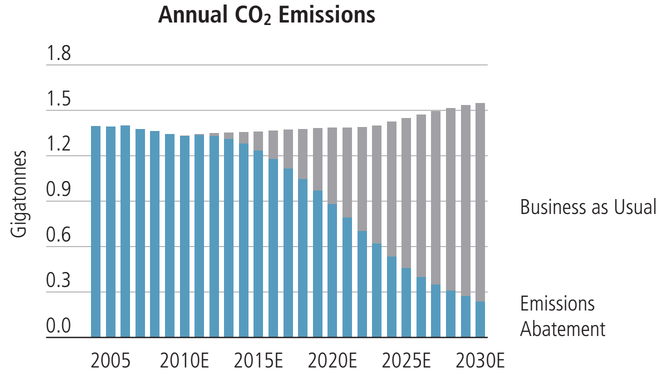
Our 2030 Forecast for Europe

By 2030, we expect developed Europe's power fleet to be generating 3.8 trillion kilowatt-hours of electricity, of which 3.6 trillion kilowatt-hours will come from clean or near-clean power sources. Europe will be almost entirely without traditional carbon-emitting coal power, but natural gas will continue to play a diminished role, producing power at peak hours. We expect that by 2030, nuclear power will be the carbon-free technology of choice, providing 35% of electricity in the region, versus 28% in 2006. Coal power will also serve as an important source of base-load supply, providing 30% of the region's electricity (*Display 98*).

The transformation of the European power fleet should result in significant emissions reductions. Today, 420 tonnes of CO_2 are emitted for every million kilowatt-hours of power produced in Europe. We expect emissions per million kilowatt-hours to plunge to 60 tonnes by 2030. Thus, over the course of our forecast period from 2006 to 2030, Europe will avoid 12 billion tonnes of CO_2 emissions from power generation and reduce annual emissions due to power by over 80% (*Display 99*). ■

Display 99

Abatement to Slash Power-Related Emissions in Europe



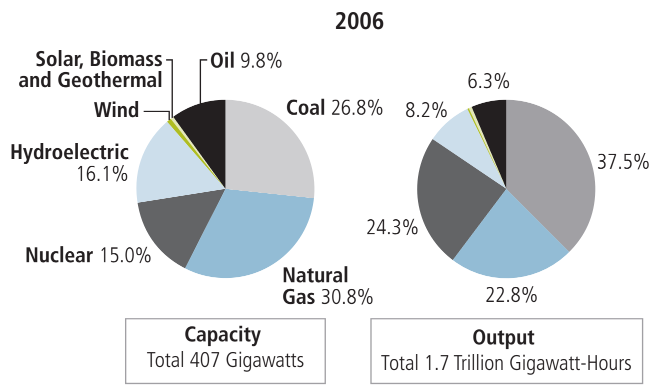
Source: EIA, IEA and AllianceBernstein

MODELING DEVELOPED ASIA'S POWER BUILD

Japan, South Korea, Australia and New Zealand, which collectively make up OECD Asia, have 407 gigawatts of electric-power capacity that generated a little less than 1.7 trillion kilowatt-hours of electricity in 2006. The largest portion of this output was from coal plants (*Display 100*), particularly in Australia, which is roughly 80% reliant on coal for power, according to the World Coal Institute. In South Korea and Japan, nuclear and natural-gas facilities complement coal. All three, plus hydroelectric power in New Zealand, are used for base-load power.

Display 100

Nuclear and Natural Gas Are Bigger in OECD Asia



Source: EIA, IEA and AllianceBernstein

Our Electricity-Demand Forecast for Developed Asia

Throughout the 1990s, developed Asia's electrical productivity fell. In 1990, these four countries produced US$3.30 of GDP per kilowatt-hour of power used. But while South Korea industrialized, extended electrical access to its population and more than doubled per-capita consumption of electricity, Japan's economy stagnated. In 2000, the four countries together were producing US$2.95 of GDP per kilowatt-hour—a decline of over 10%, over the course of the decade. In recent years, however, the regional decline in electrical productivity has been arrested. We expect it to reverse.

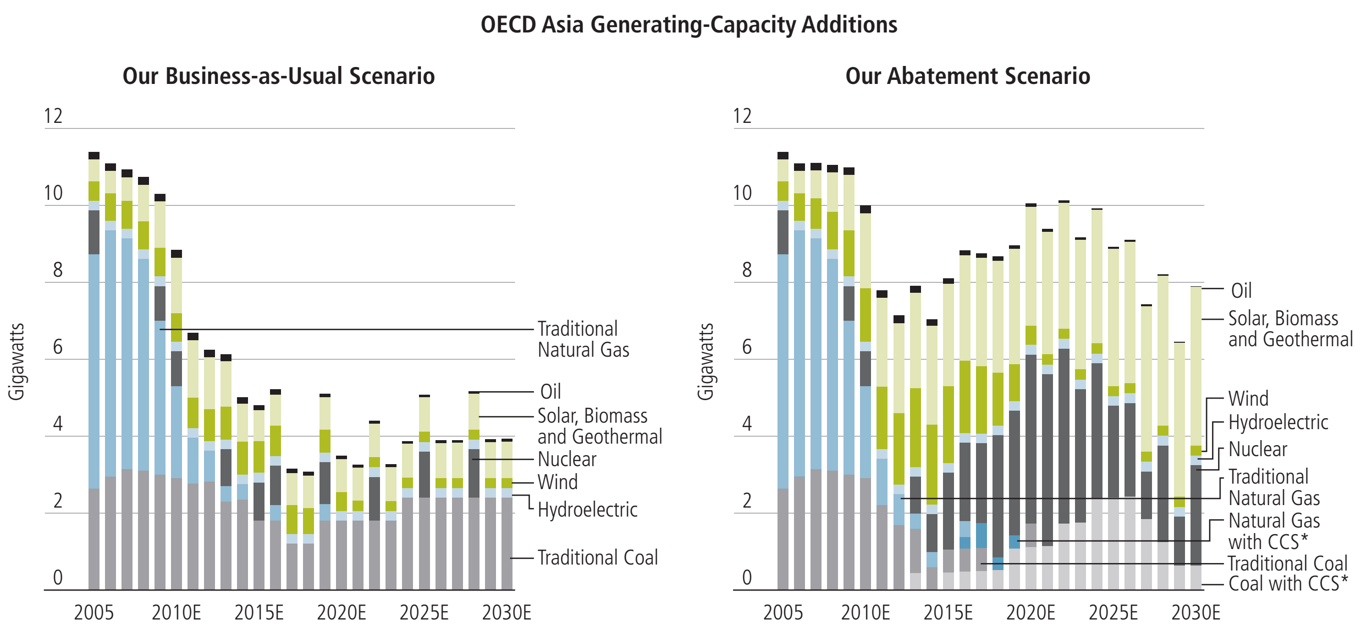
As South Korea raises its GDP per kilowatt-hour closer to the regional average and higher energy prices inspire adoption of higher-efficiency technologies, we expect developed Asia to increase its electrical productivity to over $3.30 per kilowatt-hour by 2015 and to over $4.00 by 2030. Under this scenario, developed Asia in aggregate would consume a total of 1.9 trillion kilowatt-hours in 2030.

The Build in Developed Asia

Developed Asia is rapidly building the infrastructure needed to meet increased demand for power, although the countries within the region have very different

Display 101

Climate-Change Concerns Will Transform New Build in OECD Asia Power Fleet



*Carbon capture and storage

Source: EIA, IEA and AllianceBernstein

regulatory standards (unlike members of the European Union). CO_2-emissions targets vary substantially: Japan and New Zealand have both agreed to reduce CO_2 output to 1990 levels by 2012. South Korea is not classified as an Annex I (developed) country under the Kyoto Protocol and therefore does not have a publicly announced emissions target. Australia did not ratify the Kyoto Protocol until late in 2007 and is still defining its emissions strategy.

Japanese power producers are investing in the near term in natural-gas and nuclear power, for much the same reasons as European countries. Australia is continuing to develop its coal fleet. South Korea is building a mix of fuel types to keep pace with its rapidly increasing electricity demand.

In our business-as-usual scenario, we assume that most power providers would not build natural-gas plants for base-load capacity because of the fuel's high price volatility. Thus, in the medium and long term, we assume that developed Asian countries would provide incremental capacity with coal plants, and some nuclear power and renewables to supplement the coal (*Display 101, left*).

In our abatement scenario, wind and natural gas will be used to meet demand requirements in the near term, but we expect nuclear capacity additions to reach significant levels before 2020, when much of the traditional coal infrastructure will have to be retrofitted or retired. We estimate that restrictions on carbon-emitting coal facilities, combined with the expected retirement of some nuclear facilities, will make substantial capacity additions necessary; this need may be satisfied by up to four additional nuclear-power plants a year between 2018 and 2023 (*Display 101, right*).

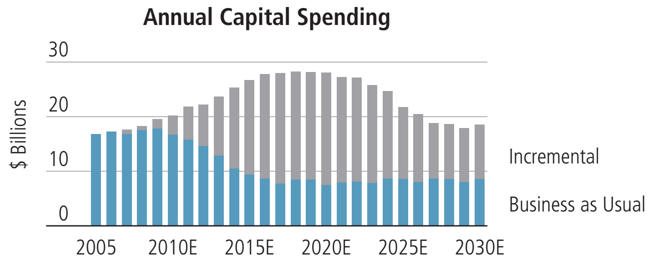
In the same period, we also expect significant investment in carbon-capturing coal and gas, retrofits of existing coal plants and a substantial commitment to solar power. We forecast that capital spending on power in the region will peak at over $28 billion a year and normalize at roughly $19 billion per year. In our business-as-usual scenario, spending would normalize at $8 billion after peaking at $18 billion (*Display 102*).

Investment Opportunity in Developed Asia

Renewable energy offers an obvious short- and medium-term opportunity in developed Asia. New Zealand has some of the best wind resources in the world but does not use a great deal of power. Japan's power grid is possibly the only one in existence built to accommodate significant solar additions. We expect

Display 102

Emissions Abatement Will Add Hugely to Power Capex in OECD Asia



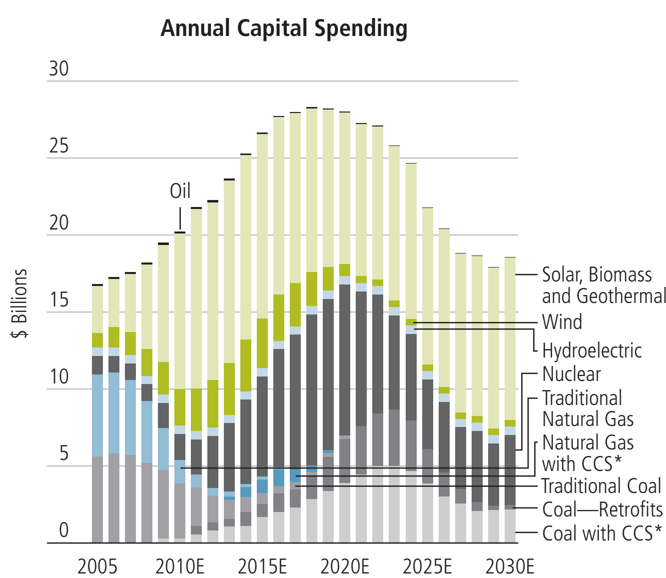
In constant 2007 dollars
Source: EIA, IEA and AllianceBernstein

spending on wind power to peak in 2015 (or earlier) as significant market penetration is curtailed by issues related to grid disruption, resource availability and transmission and distribution requirements (*Display 103*). Solar power could prove to be a more significant electricity source in the region, particularly in Japan, where an already elevated electricity price (relative to the world average) makes the technology more attractive.

We expect spending on nuclear power to increase dramatically in the short to medium term. Japan has been the only developed country in recent years to build full-scale nuclear-power facilities. Its expertise will facilitate expansion of the region's nuclear-power fleet. We expect spending to increase sevenfold against

Display 103

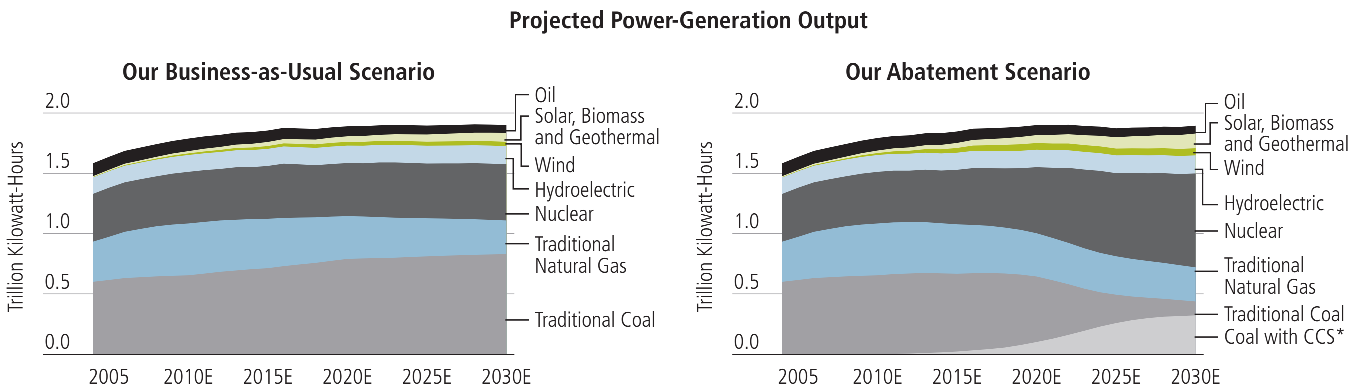
Capex on Solar and Nuclear Will Boom in OECD Asia



In constant 2007 dollars
**Carbon capture and storage*
Source: EIA, IEA and AllianceBernstein

Display 104

Abatement Will Push Power Output to Nuclear in OECD Asia



*Carbon capture and storage

Source: EIA, IEA and AllianceBernstein

our business-as-usual scenario, with capital spending on nuclear power expanding from a little over $1 billion a year in 2010 to almost $10 billion a year before 2020. Spending should remain greater than $4 billion, even after the transitional period is over.

Japan places dead last among the world's CO_2-intensive economies in preliminary geological surveys of CO_2 storage capacity. Fairly active seismic conditions are not suitable for safe storage of pressurized gases underground for hundreds or thousands of years. Similar seismic conditions prevail in South Korea. As such, these countries are less likely to rely on carbon capture and storage techniques and thus will not invest much money in carbon-capturing coal plants. Australia, which is relatively stable geologically and seems to have a great deal of storage potential, is highly likely to invest in carbon-capturing coal power, but its electricity demand is not growing as quickly as South Korea's. Thus, incremental spending on carbon-capturing power plants for the region will be significantly lower than in the other regions that we analyzed.

Our 2030 Forecast for Developed Asia

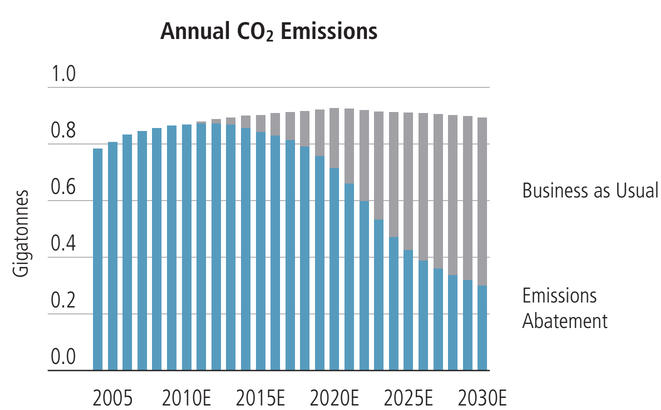
About 1.4 trillion of the 1.9 trillion kilowatt-hours that we expect to be generated by the power fleet in OECD Asia could come from clean or near-clean sources by 2030, with nuclear energy supplying 41% of total electricity generated in our abatement scenario. (In our business-as-usual scenario, by contrast, just 24% of total electricity produced in the region would come from nuclear power.) Fossil fuels would supply an additional 41%, with the remaining 18% supplied by renewable sources, with significant contributions from both hydroelectric and solar power (*Display 104*).

The power fleet in developed Asia will be more easily transformed than the fleet in the US or Europe because of local nuclear expertise and a grid well designed to accommodate renewable-energy sources. Also, the region has already implemented many effective energy-efficiency policies. Since the aggregate power demand of developed Asia is half as large as that of developed Europe and only 40% the demand of the US, the task at hand is less daunting.

Thus, we forecast CO_2-emissions reductions from the electric-power sector in the region of 65%–70% against both the business-as-usual scenario and 2006 emissions levels. This would avert emissions of 5.5 gigatonnes of CO_2 through 2030 (*Display 105*). At an average incremental capital cost of $13 billion (less than 0.2% of annual GDP), we believe that this investment is quite achievable. ■

Display 105

Power-Related Emissions Will Decline Sharply in OECD Asia



Source: EIA, IEA and AllianceBernstein

MODELING CHINA'S POWER BUILD

Chinese power generation today virtually starts and ends with coal. China is adding the equivalent of the United Kingdom's entire power fleet every year. Over the past two years, it has brought online more coal-power capacity than exists in all of developed Europe. The reasons are simple: China has ample supplies of relatively cheap coal and a ravenous appetite for electricity. Indeed, China has recently become a net importer of coal because demand in its industrial south is larger than the transportation network from its coal-rich north can support. (Improvements to the intra-regional transportation infrastructure should reduce the need for coal imports over time.)

In 2006, coal-power plants provided 467 gigawatts of power capacity in China, nearly 74% of its total power capacity and more than 81% of all electricity generated (*Display 106*). If the coal burned for electricity in China in 2006 were used for building, China could create a second Great Wall—four meters thick, seven meters high and circling the Earth.

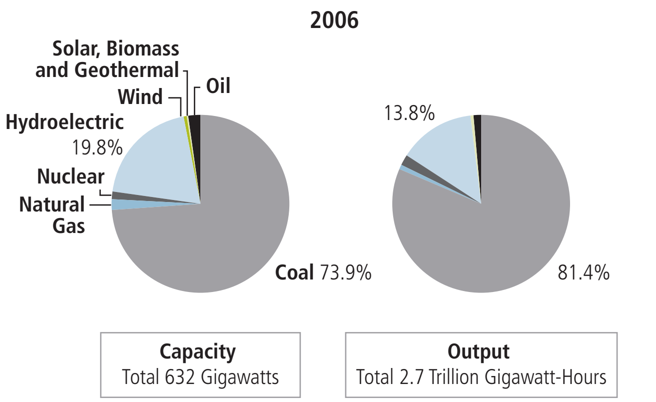
About 14% of China's electricity comes from hydroelectric power (370 billion kilowatt-hours of power in 2006). Nuclear and oil-fired generators, with 50 billion and 40 billion kilowatt-hours, respectively, make up the balance.

Our Electricity-Demand Forecast for China

The EIA predicts that before 2010, China's economy will become bigger than the US economy on a purchasing-power-parity basis. Relatively early on in our forecast period, we expect China to begin adopting energy-efficiency standards more typical of the developed world. Therefore, we predict that Chinese electrical productivity will rise from US$3.45 of GDP

Display 106

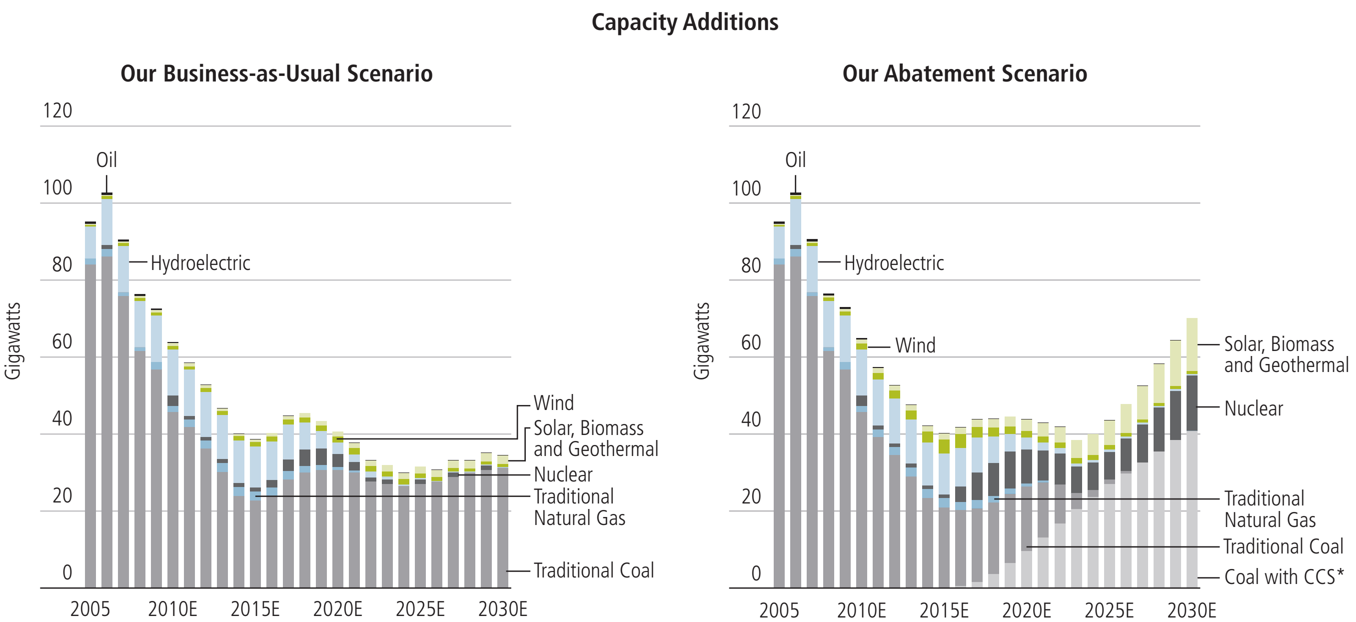
Coal Dominates Power Sector in China



Source: EIA, IEA and AllianceBernstein

Display 107

Eventually, Traditional Coal Will Even Fade from New Power Build in China



*Carbon capture and storage
Source: EIA, IEA and AllianceBernstein

per kilowatt-hour in 2006 to $5.95 per kilowatt-hour by 2030. We think that this aggressive assumption is reasonable because increasing efficiency and reducing pollution are high priorities for China's strong central government. China will also enjoy one of the advantages of being late to develop modern industrial, residential and transportation infrastructures: A large share of the country's physical plant will likely employ the most up-to-date technology and building standards.

But these efficiency increases will do little to offset China's massive growth in electricity consumption. Whereas China now accounts for only 15% of global electricity demand, we expect its share to exceed 20% by 2015 and then, with moderating growth, reach 22% by 2030.

The Build in China

China's explosive growth, enormous size and lack of credible centralized data sources lead to wide variations in industry assessments of the country's current status and trajectory. A recent MIT report, *The Future of Coal*, suggested that fully a quarter of the coal-power plants in China are not included in Chinese government statistics. As such, our anchor data, collected from colleagues in Shanghai and various Chinese companies, may prove to be imprecise. Nonetheless, we are confident that the thematic thrust of our forecast for China will hold true.

Near term, China seems to be building power capacity at such a torrid pace that capacity will soon outstrip rapidly growing demand. The central government plans to shut down 50 gigawatts of inefficient coal-power plants by 2010, which will offset some of the potential oversupply. We expect capacity growth to moderate over the next five years, whether or not emissions-abatement policies are adopted.

China will continue to build out its hydroelectric capacity. Only 24% of China's potential hydroelectric capacity has been exploited, according to an official release by Zhang Guobao, deputy chairman of the State Development and Reform Commission. The government aims to exploit 50%, for a total of 294 gigawatts, by 2020.[128] We think that this goal is slightly overoptimistic: We estimate that China will have 264 gigawatts of hydroelectric capacity by 2020. We expect hydroelectric installations to grow much more slowly after 2020, as the political and environmental issues raised by large-scale hydroelectric projects make execution less palatable.

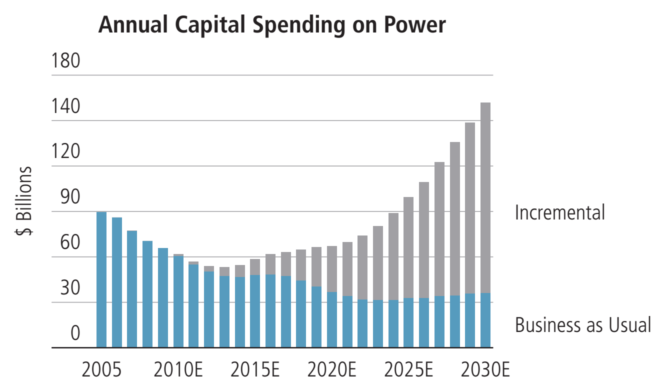
In the near term, we expect that any post-Kyoto global agreement on CO_2 emissions will be relatively lenient with regard to developing countries. Thus, China's transition to clean power will likely be more gradual than the transition made by developed nations. Our forecast assumes continued construction of traditional coal-power plants in China into the 2020s, well after it halts in developed markets (*Display 107, previous page*).

We also expect China to be relatively slow to adopt carbon-capturing coal-power technology and reluctant to retrofit or retire existing carbon-emitting plants. But once firm restrictions are in effect, probably about 2017–2019, we expect a relatively rapid about-face. China has already established aggressive mandates for nuclear and renewable power, and will likely begin planning for clean coal reasonably soon. Thus, we expect capital expenditures to grow rapidly again in the medium to long term (*Display 108*).

In our business-as-usual scenario, China's power producers do not return to today's capital spending of $90 billion a year by 2030. In our emissions-abatement scenario, capital spending on power almost doubles, to $160 billion a year by 2030, because of the increased capital costs of carbon-capturing coal, coal retrofits, nuclear facilities, and wind and solar relative to traditional coal, as well as spending to offset premature retirements and efficiency losses due to retrofits. We expect far-ranging implications from this huge expenditure.

Display 108

Abatement Will Sustain Huge Power Capex in China

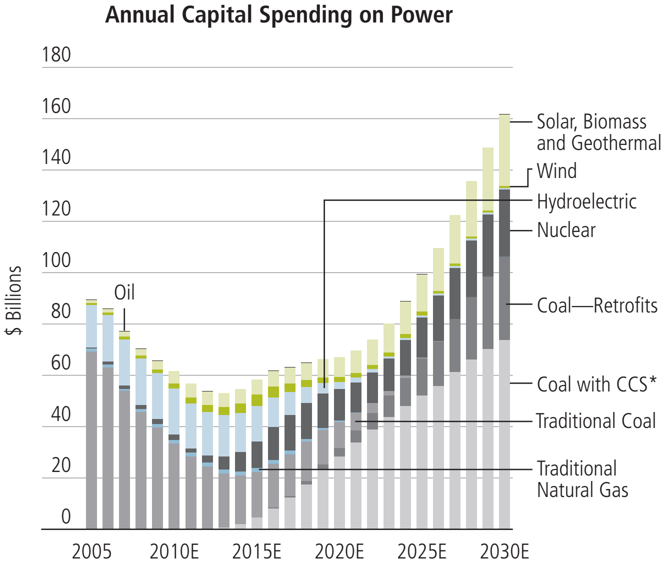


In constant 2007 dollars
Source: EIA, IEA and AllianceBernstein

[128] http://www.renewableenergyaccess.com/download/2007-02-China-RE-Report.pdf

Display 109

Abatement to Spur Chinese Spending on Clean Coal and Gas



In constant 2007 dollars

**Carbon capture and storage*

Source: EIA, IEA and AllianceBernstein

Investment Opportunity in China

We expect incremental spending on nuclear-power capacity to increase relatively quickly because the Chinese government has made it a strategic priority. Although we do not expect China to face strict carbon-emissions standards for 10 years, the government wants to develop China's power industry, diversify its fuel sources and reduce pollution. We foresee capital spending on nuclear power rising from $3 billion in 2012 to $14 billion by 2018, a 30% compound annual growth rate (*Display 109*).

Hydroelectric power will dominate spending on renewable energy for at least the next decade, but there is also a near- to medium-term growth story in solar and wind power. We expect the Chinese government to set targets for renewable-energy generation. Hence, Chinese solar companies will soon begin marketing their products domestically for use in new construction. Chinese infrastructure companies are also trying to develop wind-power expertise. Spending on wind should accelerate over the next five years with solar-power spending soaring over the long term, rising from $4 billion in 2010 to over $25 billion by 2030.

Given the massive size of China's coal-power fleet, any systemwide transformation of coal-power-generation equipment will have considerable economic impact. We expect capital spending on coal power to increase more than fivefold between 2015 and 2030, with Chinese power producers spending over $100 billion annually on coal retrofits and new carbon-capturing coal plants.

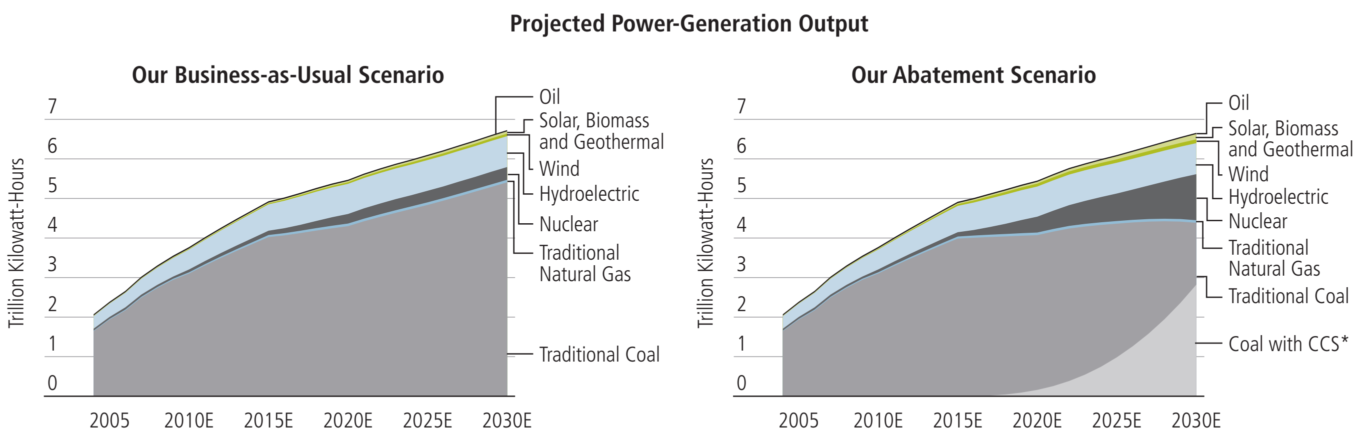
Our 2030 Forecast for China

In our business-as-usual scenario, China alone would burn 75% as much coal in 2030 as the entire world does today. But since we expect carbon-emissions regulations to make traditional coal-burning plants significantly less attractive, we expect to see a significantly larger role for nuclear energy in China by 2030. We also predict that many of China's large-scale coal-power plants will be shut down or retrofitted to capture carbon dioxide. By 2030, 42% of China's power will come from clean coal (*Display 110*).

Carbon-capturing coal-power plants will thus become the largest and most rapidly expanding source of power in the Chinese electric grid during our forecast period.

Display 110

Abatement Will Push Output to Clean Coal and Nuclear in China



**Carbon capture and storage*

Source: EIA, IEA and AllianceBernstein

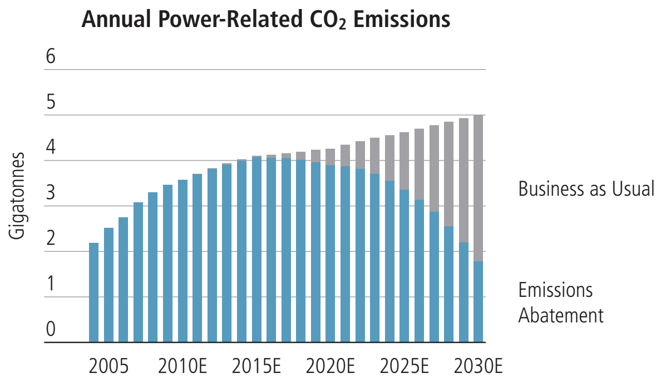
Nuclear power will also grow robustly, and traditional coal as well as hydroelectric power will continue to supply significant amounts of base-load electricity. Although wind-generation capacity will grow and current solar-generation capacity will grow very rapidly, these sources are likely to be incapable of satisfying a substantial portion of China's electricity needs, barring a significant technological breakthrough.

China will soon emit more CO_2 than any other country, if it does not already do so. The annual difference in the Chinese power-fleet emissions in 2030 in our abatement scenario versus the business-as-usual case is over 3.2 gigatonnes of CO_2 (*Display 111*). That is huge: The entire global fleet of light-duty vehicles emitted "only" 2.8 gigatonnes of CO_2 in 2006.

By applying the proposed transformation to its power fleet, China could abate 17 gigatonnes of CO_2 by 2030. In the same time frame, China is expected to generate over $550 trillion in GDP. While it is said that China will not move until the world moves, if China does move aggressively, it could change the world. ■

Display 111

Ultimately, Power-Related Emissions Will Decline in China



Source: EIA, IEA and AllianceBernstein

MODELING INDIA'S POWER BUILD

India, like China, relies heavily on abundant local supplies of coal for electricity: Over 70% of the country's 670 billion kilowatt-hours of electricity generated in 2006 came from coal (*Display 112*). India also has significant hydroelectric potential. Despite political considerations that have impeded development in recent years, hydroelectric power accounted for 15% of the electricity produced in India in 2006. Nuclear and natural-gas generation commanded roughly equal shares of the remaining output; both have grown recently.

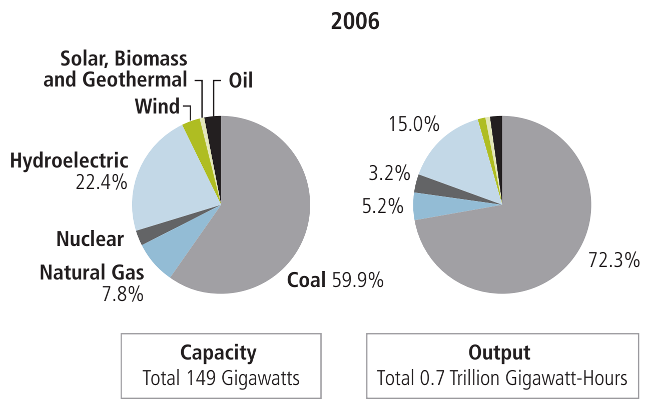
Our Electricity-Demand Forecast for India

India is expected to continue growing rapidly: The EIA expects its GDP to soar from $4.3 trillion in 2006 to over $15 trillion in 2030.

Electricity consumption is low relative to GDP because roughly 600 million—more than half—of India's 1.1 billion people do not have access to electricity today, according to the Planning Commission of India. Most people who have access to electricity endure frequent outages that reduce consumption and disrupt the economy. Per capita, India consumes roughly 5% as much electricity as the US. As India addresses its infrastructure shortfall, power consumption should dramatically increase.

Display 112

Coal Dominates Power Capacity and Generation in India

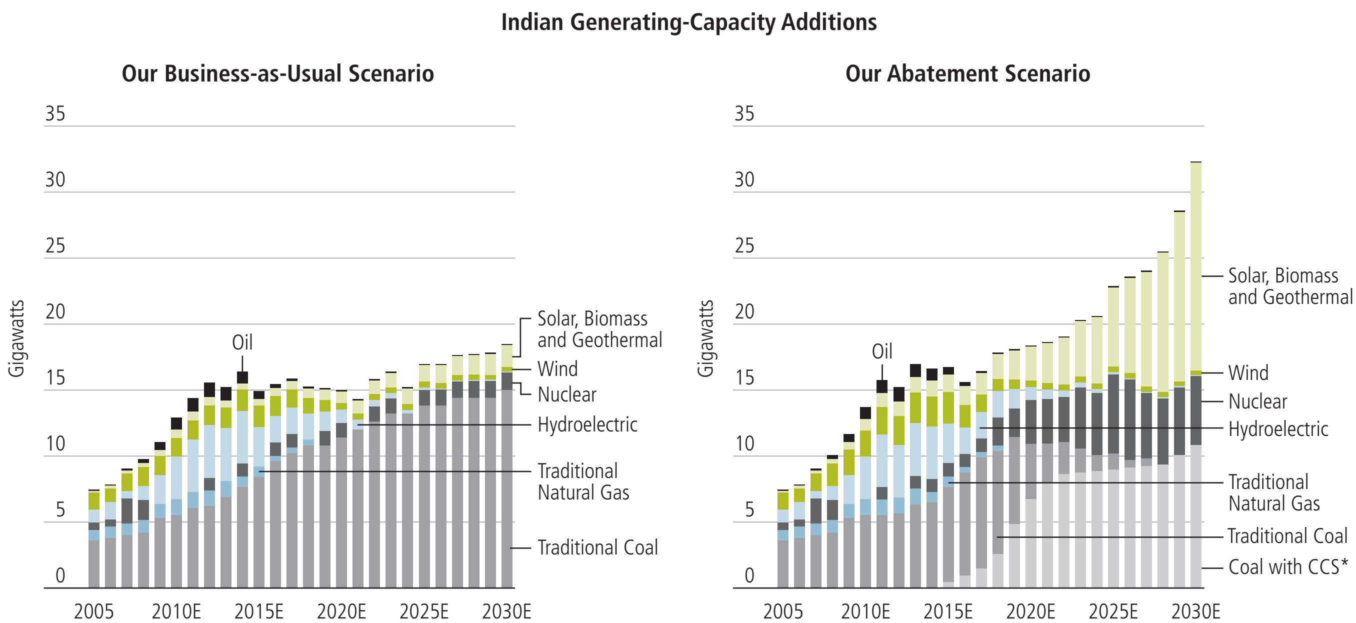


Source: EIA, IEA and AllianceBernstein

It remains unclear how India will address its infrastructure shortfall: Capital is not abundant, and India, unlike China, does not tend to embark on massive centrally planned projects. Although we expect India to make headway, it is likely that even toward the end of our forecast period, a significant portion of the population will not have access to electricity.

Display 113

Climate-Change Concerns Will Transform New Power Build in India



**Carbon capture and storage*
Source: EIA, IEA and AllianceBernstein

It is also likely that the growing market for electric power in India will adopt efficient systems and products that further restrain per-capita power consumption. By 2030, we expect Indian power producers to generate 2.6 million kilowatt-hours of electricity, or less than two megawatt-hours per person, up from 0.63 megawatts hours per person in 2006, but still far below the 13 megawatts per person in the US.

The Build in India

Peak electricity demand exceeds supply in India by roughly 12%, the country's Planning Commission says. The government is struggling to establish a framework to encourage development of power infrastructure. India, like China, has an abundance of coal and plentiful hydroelectric resources. In the near term, these two power sources will almost certainly dominate efforts to meet burgeoning demand.

In our business-as-usual scenario, coal would remain king (*Display 113, left, previous page*). We expect power producers to continue to rely on this economical fuel source to meet demand in slowly electrifying rural areas and increasingly dense urban markets. Hydroelectric resources will likely be developed until the most productive sites are utilized.

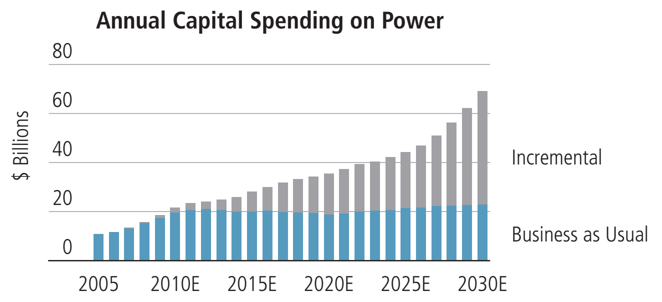
Eventually, CO_2-emissions regulations are likely to provide incentives for power producers to adopt various clean technologies, in addition to hydroelectric power. As a developing nation, India is not likely to be required to adopt such technologies for another decade or so. By 2020, however, Indian power producers are likely to begin making significant commitments to both carbon-capturing coal and nuclear infrastructure (*Display 113, right, previous page*). We also expect regulation to prompt carbon-capture retrofits, to beginning in about 10 years. In time, we believe that Indian power producers will devote themselves almost exclusively to building the triumvirate of solar, carbon-capturing coal and nuclear power.

In the near term, we expect spending on power to surge as producers seek to cover the supply shortfall and exploit hydroelectric resources. In a business-as-usual scenario, this short- to medium-term infrastructure boom would likely diminish in five to 10 years, after power producers developed massive amounts of low-cost coal facilities and quick, but suboptimal, solutions to transmission and distribution bottlenecks.

In our abatement scenario, the near-term spending boom will likely be surpassed in the medium to long term, when companies begin spending on coal retro-

Display 114

Abatement to Sustain Strong Capex Growth in India



In constant 2007 dollars
Source: EIA, IEA and AllianceBernstein

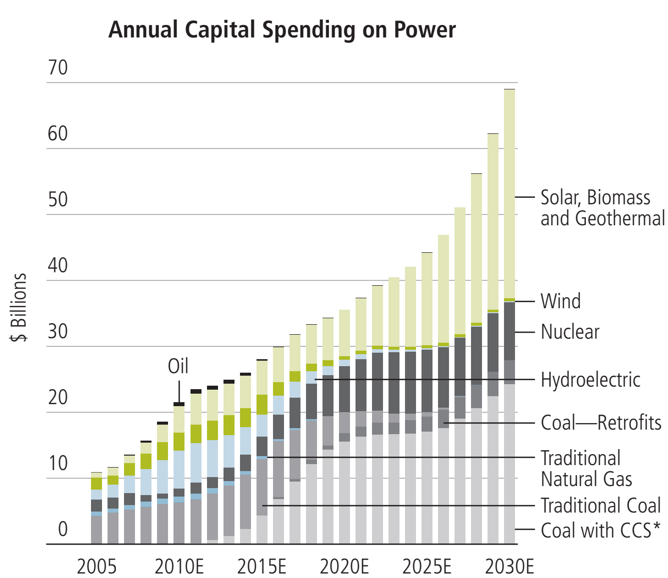
fits, new carbon-capturing coal plants, nuclear energy and solar power. We expect to see power-generation spending of about $70 billion a year by 2030, triple the peak in our business-as-usual scenario (*Display 114*).

Investment Opportunity in India

Money will be invested in wind and solar power, but given the severe power shortage, devoting scarce capital to such inefficient projects seems impractical, at least until solar energy becomes more cost-effective. Hydroelectric projects, however, will likely be developed aggressively. Since these resources and the political will to exploit them are finite, we foresee hydroelectric-power spending peaking before 2015 (*Display 115*).

Display 115

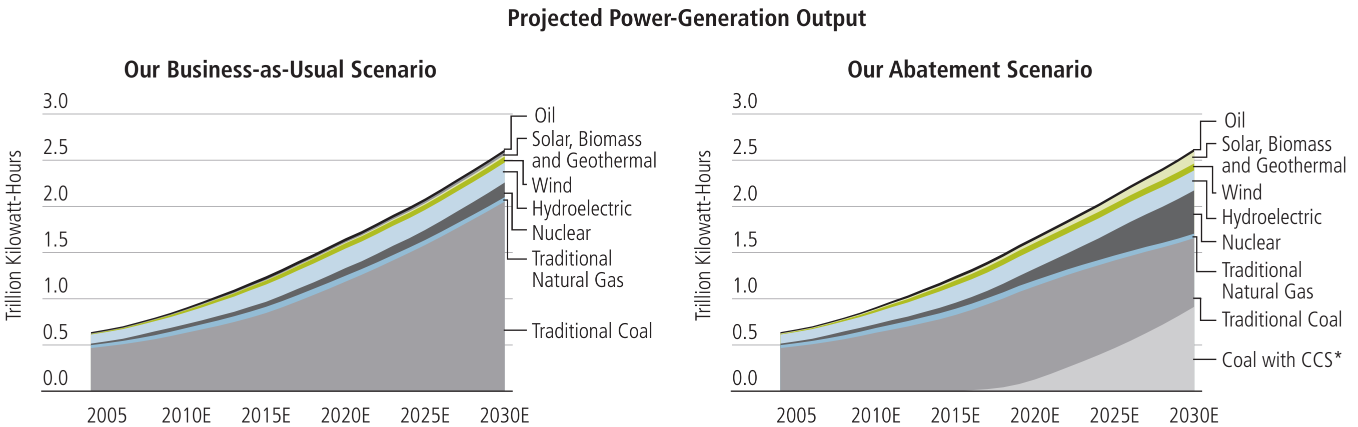
Abatement to Spur Spending on Clean Coal and Solar in India



In constant 2007 dollars
* *Carbon capture and storage*
Source: EIA, IEA and AllianceBernstein

Display 116

Abatement Will Push Output to Clean Coal and Nuclear in India



**Carbon capture and storage*
Source: EIA, IEA and AllianceBernstein

Meaningful amounts will be spent on traditional coal plants in the near term. In the medium term, spending on clean coal will accelerate. Once carbon-emissions regulations are in effect, capital spending on clean coal will likely grow at about a 10% annual rate between 2015 and 2020, compared with the 5% rate of spending on coal overall in our business-as-usual scenario.

We predict that nuclear power will be the true growth opportunity in the Indian power market. Beginning in 2010 and continuing into the 2020s, we expect nuclear power's relatively low cost and suitability for base-load capacity to make it very attractive to the Indian government. The Indian government has recently begun negotiations to purchase enriched uranium from the US; we expect these negotiations to lead to capital-spending growth on nuclear power of over 20% a year from 2010 to 2020.

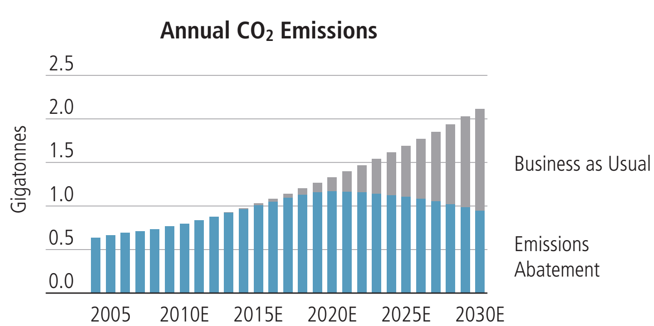
Our 2030 Forecast for India

India's need for new power infrastructure is pressing, regardless of concerns about greenhouse-gas emissions. In May 2007, India's prime minister identified electricity shortages as the single biggest threat to the country's economic growth.[129] This makes it less likely that India will take near-term steps to reduce CO_2 emissions. Once the immediate shortfall is resolved and proper financial incentives are in place—probably by about 2015—Indian power producers will likely focus on abating CO_2 emissions. In our abatement scenario, we project that India could generate 70% of its power from clean and near-clean sources by 2030, compared with just 20% in our business-as-usual scenario (*Display 116*).

India stands apart from the other regions examined in our research: Its total emissions will be higher in 2030 than in 2006. However, the way in which India develops its infrastructure will significantly affect CO_2-emissions levels in the second quarter of the twenty-first century. By developing nuclear capacity, starting to retrofit existing coal facilities, building new carbon-capturing coal plants and exploiting the country's vast hydroelectric resources, India's power fleet could increase electrical output by 90% by 2030 while only emitting 21% more CO_2 than it did in 2006 (*Display 117*). Our business-as-usual model, by contrast, calls for emissions from power generation in 2030 almost triple their level in 2006. ■

Display 117

Ultimately, Power-Related Emissions Will Decline in India



Source: EIA, IEA and AllianceBernstein

129 http://www.thebusiness.co.uk/the-magazine/columns/33908/india-to-tackle-chronic-power-shortages-by-going-nuclear.html

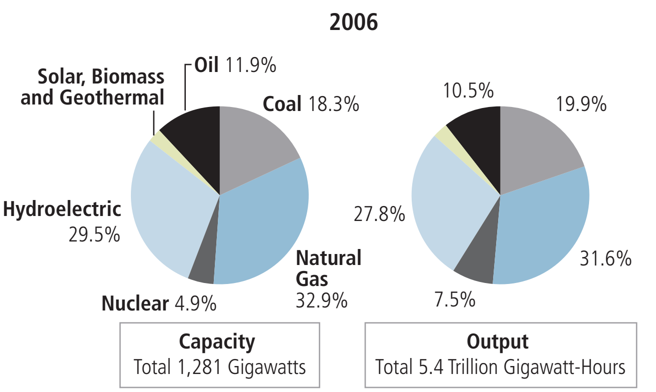
MODELING THE REST OF THE WORLD'S POWER BUILD

For the purposes of our research, "Rest of World" includes the eclectic mix of countries not otherwise analyzed. It includes coal-rich countries such as Canada, Mexico and South Africa, the oil- and natural-gas-rich Middle East and Russia, and Central and South America, where several countries exploit abundant hydroelectric resources.

Far more of this group's electricity—over 40%—comes from burning either oil or natural gas than any other region's (*Display 118*). This reflects the abundant, cheap supply of these fuels in many countries. Hydroelectric, coal and nuclear power provide most of the rest.

Display 118

Oil and Natural Gas Are Key to Rest of World Power Sector



No wind power in 2006
Source: EIA, IEA and AllianceBernstein

This conglomeration of nations, which accounted for almost half the world's population in 2006, generated 5.4 trillion kilowatt-hours of electricity, roughly 30% of the world's total that year. The three nations in the group that generated the most power—Russia, Brazil and Canada—accounted for more than half the group's total.

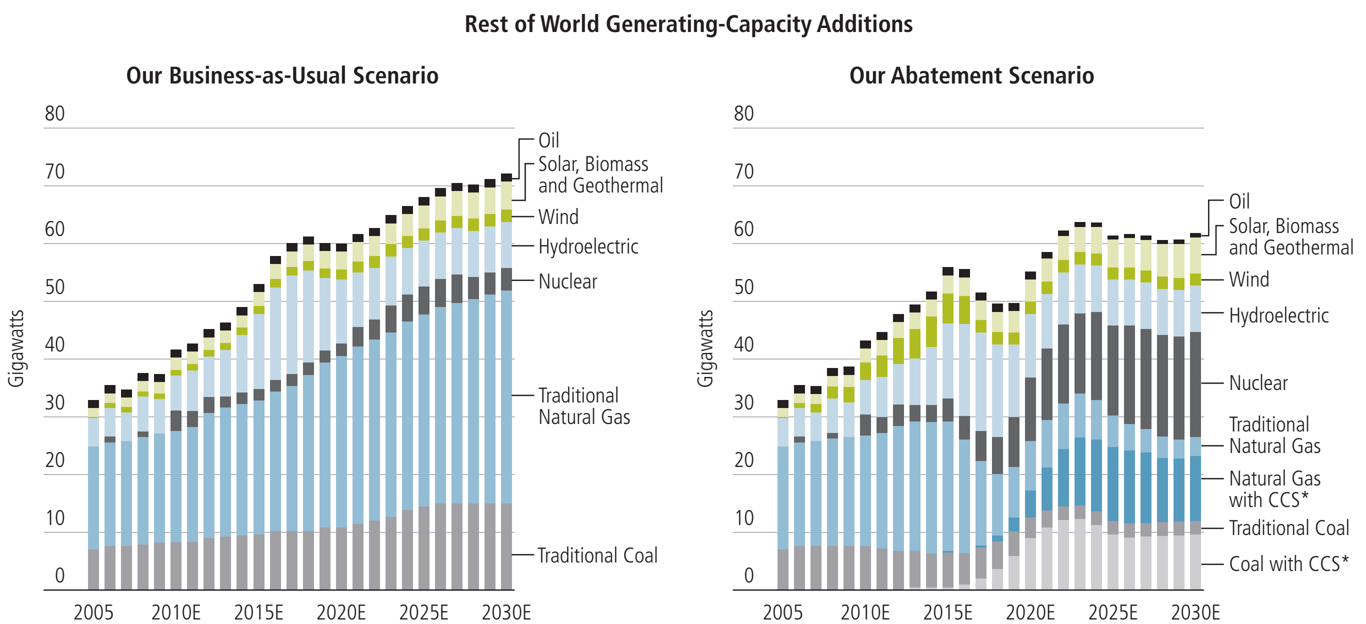
Our Electricity-Demand Forecast for the Rest of the World

The EIA projects that this group's economic output will grow at a compound annual rate of 4.2% until 2030, up from its 2.6% growth rate between 1980 and 2004. Strong growth in developing Africa, Eastern Europe and developing Asia (4.9%, 4.9% and 4.6%, respectively) will be partly offset by slower growth in developed countries such as Canada (2.9%) and transitional countries such as Brazil and Russia (3.4% and 3.7%, respectively).

Electricity use tends to correlate with GDP, so we expect strong growth in electricity generation and consumption for the group, led by the extension of electricity service in developing nations. In Africa, we expect per-capita electricity consumption to increase by almost 50% by 2030, while its population increases by more than 500 million

Display 119

Climate-Change Concerns Will Transform New Build in Rest of World



**Carbon capture and storage*
Source: EIA, IEA and AllianceBernstein

(or more than 60%). In Canada, Brazil and Russia, on the other hand, increased efficiency will slow demand growth. Taking these conflicting trends into account, we estimate compound annual growth in electricity generation of 2.6% a year for the region. Based on this estimate, we calculate that this collection of countries will consume about 10 trillion kilowatt-hours in 2030.

The Build in the Rest of the World

Reliable access to natural gas has prompted Russia and the Middle East to pursue a power-infrastructure path requiring relatively low capital investment. Coal-rich countries, such as South Africa, have continued to invest in coal power, while many South and Central American and Asian countries have focused on developing their abundant hydroelectric resources. We expect these trends to continue in the short to medium term, regardless of carbon-emissions policies adopted elsewhere.

Without carbon-emissions restrictions, this investment pattern would likely continue, with Russia and Canada also deploying their nuclear expertise to build additional power plants (*Display 119, left*).

Our abatement scenario looks quite different, with far more nuclear power and clean coal (*Display 119, right*). South Africa, Russia and Argentina have already begun planning new nuclear facilities. We expect Canada (a signatory of the Kyoto Protocol) to move at least as quickly as the US in developing clean coal technologies, despite Canada's dubious distinction of being second only to Japan in terms of failing to meet its Kyoto emissions-reduction target. South Africa, which now has seven of the world's 70 largest stationary sources of CO_2 emissions, will also come under heavy pressure to adopt clean coal technologies. Thus, coal-fleet additions in this group of countries will largely be carbon-capture-ready by 2020.

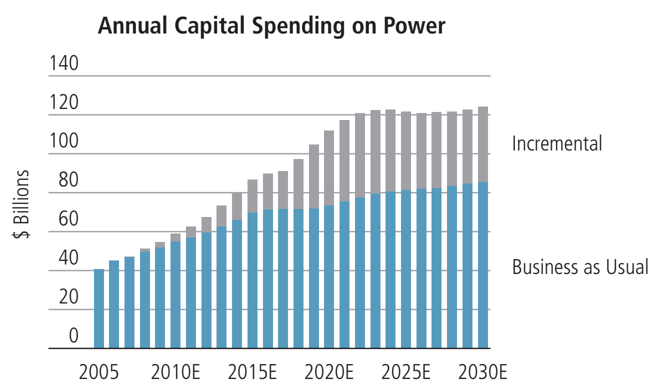
Countries dependent on natural gas will face a dilemma if global regulations impose a cost on all CO_2 emissions because adding carbon-capture technology would significantly reduce the capital-cost advantage of natural-gas power. It would also reduce natural gas's environmental edge: Natural-gas plants without carbon capture emit only half as much CO_2 as coal plants without carbon capture; with carbon capture, the two fuel sources have virtually identical emissions profiles. Our research suggests that carbon-capturing natural-gas plants will be economical only in areas where gas is so cheap and abundant that it can be readily used for base-load power—that is, in the Middle East and Russia.

In other regions, carbon regulation will make natural-gas facilities uneconomic. Thus, the natural-gas build rate after 2020 will be somewhat restrained in our abatement model compared with our business-as-usual model. Nuclear power will fill most of the gap, at least in the larger countries with governments that can provide the necessary oversight to satisfy international concerns about the risk of terrorism and nuclear proliferation.

As a result of this mix shift, capital spending by the group is about 50% higher in our abatement model than in our business-as-usual model by 2020, and we expect it to remain elevated (*Display 120*).

Display 120

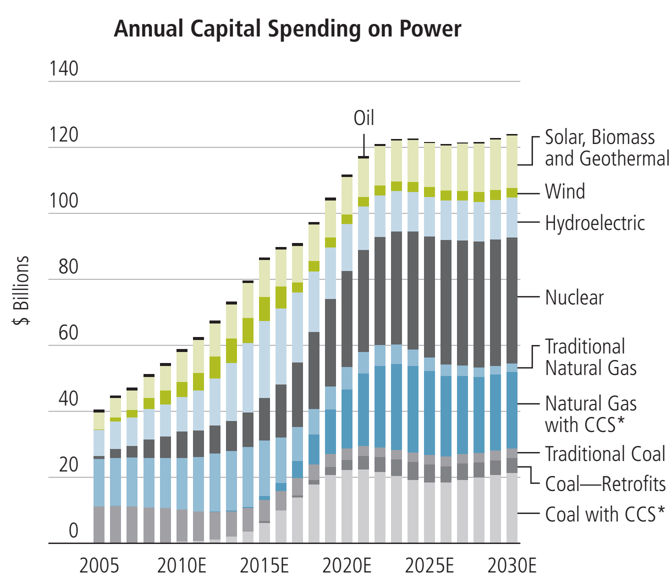
Abatement to Sustain Capex Growth in Rest of World



In constant 2007 dollars
Source: EIA, IEA and AllianceBernstein

Display 121

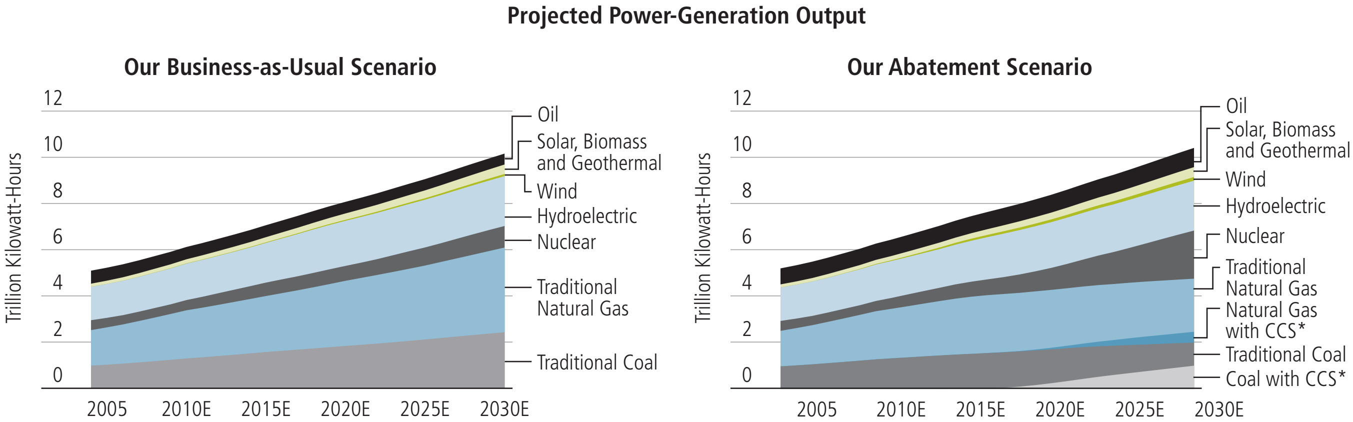
In Rest of World, Abatement to Spur Clean Gas Capex



In constant 2007 dollars
**Carbon capture and storage*
Source: EIA, IEA and AllianceBernstein

Display 122

Abatement Will Push Power Output to Nuclear in Rest of World



*Carbon capture and storage

Source: EIA, IEA and AllianceBernstein

Investment Opportunity in the Rest of the World

We expect substantial investment in nuclear power, especially in the medium term (*Display 121, previous page*). Capital spending on nuclear power will compound at greater than a 10% rate from 2015 through 2020. Canada, Russia, South Africa and several Eastern European and Asian nations already have nuclear-power plants. Some developed countries are likely to provide nuclear-power technology and support to developing nations in the group as bargaining chips to encourage nuclear-proliferation controls.

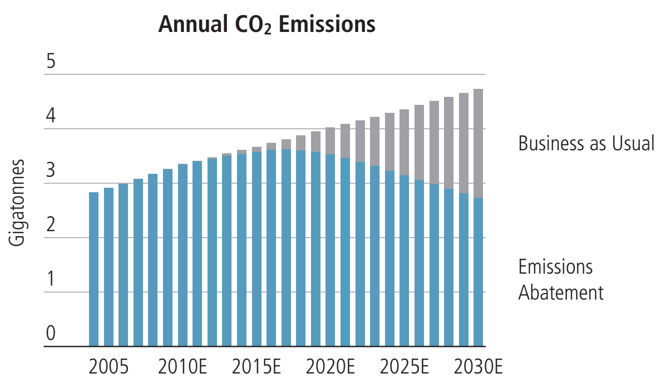
These countries are unlikely to invest much in renewable energy except for hydroelectric power in the short to medium term. Most of them cannot afford the subsidies required to spur this relatively uneconomic investment. It is possible that over the long term, distributed solar power will spread into nations that do not have the resources to develop a nationwide power infrastructure, but we do not incorporate this scenario into our forecast.

Our 2030 Forecast for the Rest of the World

We expect this conglomeration of countries to derive a significant portion of its electric-power output from clean or near-clean technologies by 2030 (*Display 122*). Reliance on hydroelectric power and natural gas, which is relatively clean, already causes the carbon-emissions profile of the group to be relatively low, at 560 tonnes per million megawatt-hours. We expect the group to reduce the carbon-emissions intensity of its power fleets to less than 270 tonnes per million megawatt-hours by producing over 60% of their electricity with clean or near-clean power sources. Thus, electricity-related CO_2 emissions for the group in 2030 will be more than 40% lower in our abatement scenario than in our business-as-usual scenario (*Display 123*). ■

Display 123

Ultimately, Power-Related Emissions Will Fall in Rest of World



Source: EIA, IEA and AllianceBernstein

Appendix B:

Our CO_2-Emissions Model

One key goal of our research was to look beyond the global power fleet to determine how CO_2 regulations would affect global CO_2 emissions across all economic sectors and how reduced emissions would affect atmospheric concentrations of CO_2.

Two primary assumptions drove our CO_2-emissions estimates:

- GDP growth is the primary driver of energy use and therefore growth in emissions; and
- CO_2 regulations will apply first to power generation and then, with a lag, to other sectors of the global economy.

The Sources of CO_2 Emissions

The most recently available definitive global CO_2-emissions data come from 2003. The emissions information is divided into categories, as required by the IPCC's Common Reporting Framework.[130] We derived a forecast from this anchor data and consolidated the categories for ease of analysis (*Display 124*).

Display 124

How We Consolidated the IPCC's Categories of Emitters

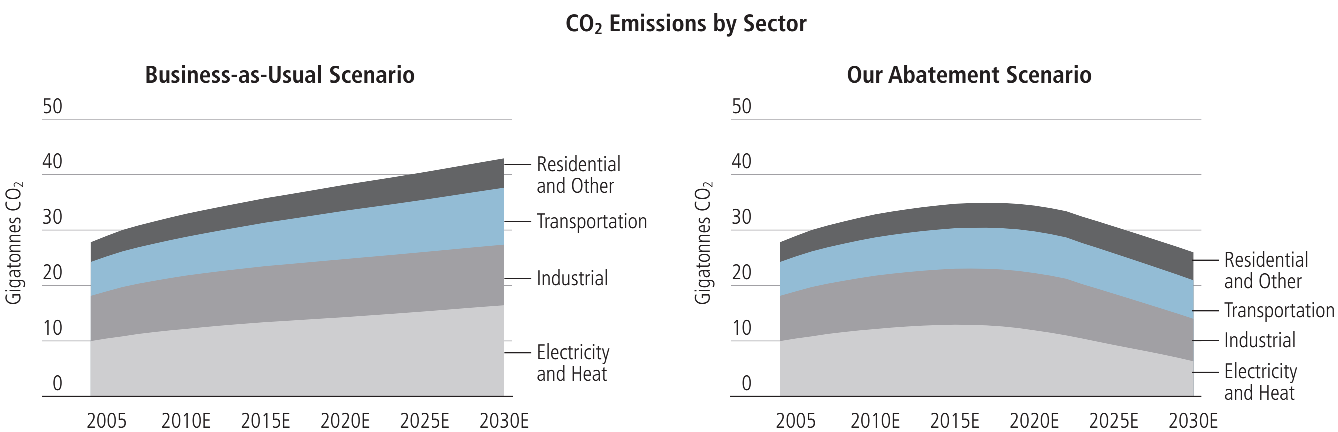
Gigatonnes CO_2

IPCC Category		**AB Category**	
Electricity & Heat	9.03	Electricity & Heat	9.03
Manufacturing & Construction	0.99	Industrial	7.77
Unallocated Autoproducers	1.26		
Other Energy Industries	4.51		
Industrial Processes	1.01		
Transportation	5.12	Transportation	5.94
International Bunkers	0.82		
Other Fuel Combustion	3.26	Residential & Other	3.41
Fugitive Emissions	0.15		
Total	**26.15**		**26.15**

Source: IEA, IPCC and AllianceBernstein

Display 125

Abatement Efforts Will Lead to Emissions Drop in All Sectors Except Residential



Source: EIA, IEA and AllianceBernstein

[130] Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories

Electricity and Heat Sector Emissions. This category is central to our model of the power fleet, which accounts for emissions per megawatt-hour for each type of fossil-fuel-burning plant. The values vary regionally, depending on the average efficiency of the local power plants and the quality of the fuel available in the region. Throughout the forecast period, in both our business-as-usual and our emissions-abatement scenarios, we assume that even traditional (that is, non-carbon-capturing) technology would gradually become less carbon-intensive.

Average CO_2 emissions for coal-burning plants range by region from 0.9 to 1.3 tonnes per megawatt-hour, while emissions from natural-gas plants range from 0.45 to 0.75 tonnes per megawatt-hour. Emissions for oil-burning plants are 0.7 to 1 tonne per megawatt-hour. For carbon-capturing coal and natural-gas facilities, we assumed that 90% of emissions would be captured and stored. Overall, emissions from the electricity and heat sector begin to fall in 2015 (*Display 125, previous page*).

Industrial Sector Emissions. For our business-as-usual forecast, we examined regional emissions rates for each category relative to GDP and forecast evident secular trends forward. Average annual emissions per dollar of GDP falls by 3% over the course of our forecast period.

For our abatement scenario, we assumed eventual adoption of CO_2 capture and storage by large-scale industrial emissions sources in much the same way as in power plants. Often, CO_2 streams emitted by industrial facilities are more concentrated than those emitted by generating plants, and therefore carbon capture is easier. We estimated that 65% of industrial emissions come from stationary sources large enough to justify the capital investment and energy requirements for CO_2 capture and storage.

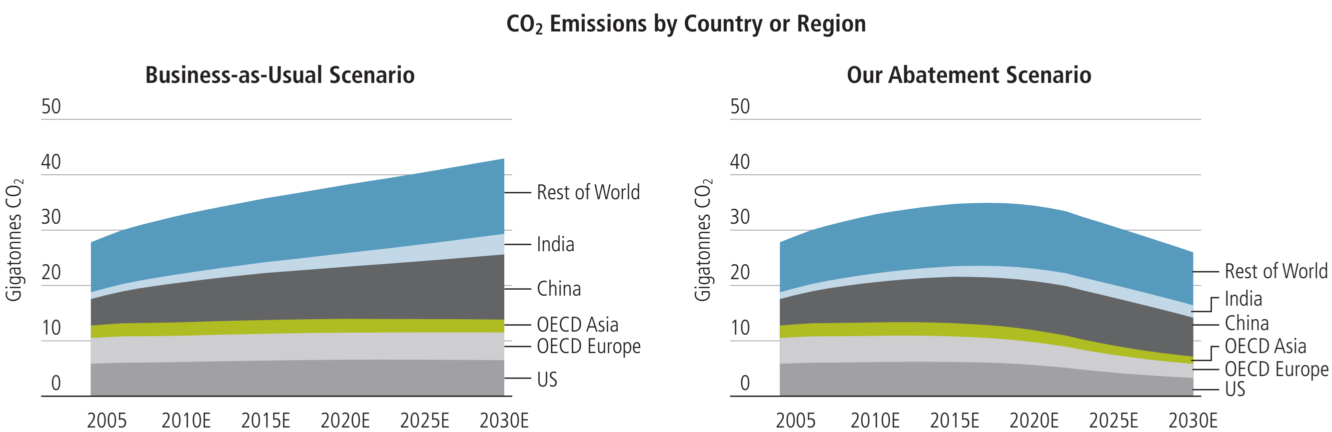
But we also factored in a delay in CO_2-emissions reductions for industry, assuming that many countries will, like the EU, delay imposing emissions regulations on industry in order to protect local companies that operate in the global marketplace and therefore likely have competitors in developing regions that are not subject to the same restrictions. Thus, in our emissions-abatement scenario, we assumed that large-scale industrial emitters begin reducing emissions four years after regulations go into effect for the region's electric utilities.

Transportation Sector Emissions. Our emissions-abatement forecast for this sector is largely based on our previous research into hybrid vehicles.[131] Based on this study, we believe that there will be large-scale adoption of plug-in hybrids within the light-duty vehicle fleet by 2030. For our emissions-abatement scenario, we also assume that other road transport vehicles, including trucks and buses, adopt hybrid electric technology and gain 65% of the fuel-efficiency increase experienced by the light-duty vehicle fleet.[132]

Residential Sector and Other Emissions. To reach our business-as-usual forecast for residential emissions, we took a similar approach as for industrial emissions: We investigated recent regional trends in residential-emissions intensity relative to GDP. As a result, we

Display 126

Abatement Efforts Will Lead to Emissions Drop in All Regions



Source: EIA, IEA and AllianceBernstein

[131] Raskin and Shah, "The Emergence of Hybrid Vehicles"

[132] Our electricity-demand projections incorporated the additional 2.9 trillion kilowatt-hours that would occur with the projected level of plug-in hybrid adoption.

reduced emissions per dollar of GDP by roughly 2% over the course of the forecast period.

We do not expect CO_2-related regulations to have a sizable impact on this sector. As a result, we only modestly increased the intensity reduction over the course of the forecast.

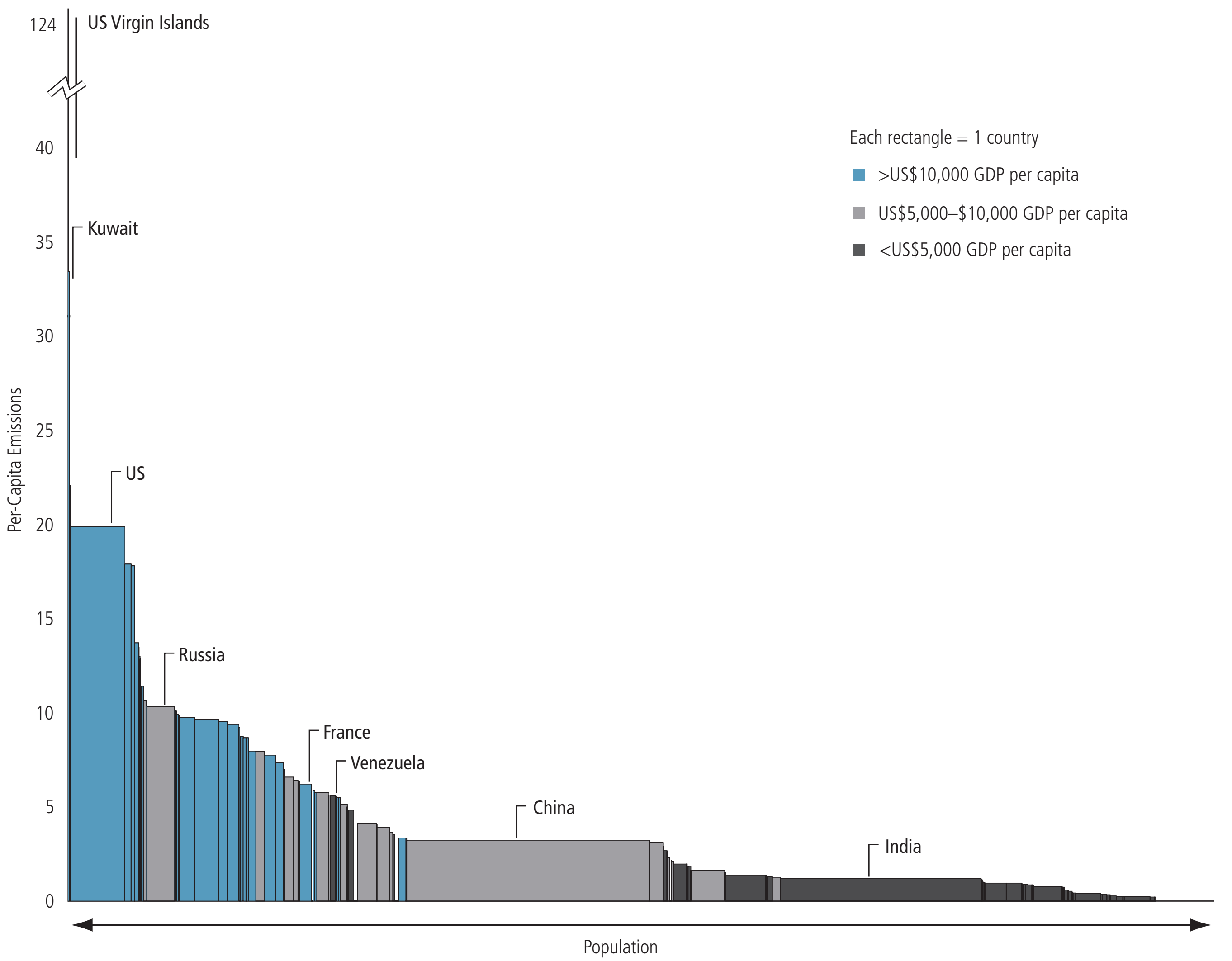
Emissions by Region

In our business-as-usual case, we expect annual global emissions of CO_2 to hit 43 gigatonnes by 2030, with a large share of that (16.4 gigatonnes) coming from power generation (*Display 126*). In our abatement scenario, we expect global emissions to fall to 25.9 gigatonnes of CO_2 by 2030, below 2006 levels. Furthermore, we expect developed countries collectively to emit only 66% of their 1990 emissions levels in 2030.

We expect China to become the world's largest emitter in 2007. It should come as no surprise: As countries develop economically, they tend to emit more CO_2 per person. With China's massive population, even a moderate increase in CO_2 emissions per capita would result in a tremendous increase in total CO_2 emissions. For a sobering exercise, examine *Display 127* and imagine India and China approaching even half the per-capita emissions of the US. We do not expect that to occur in the foreseeable future.

Display 127

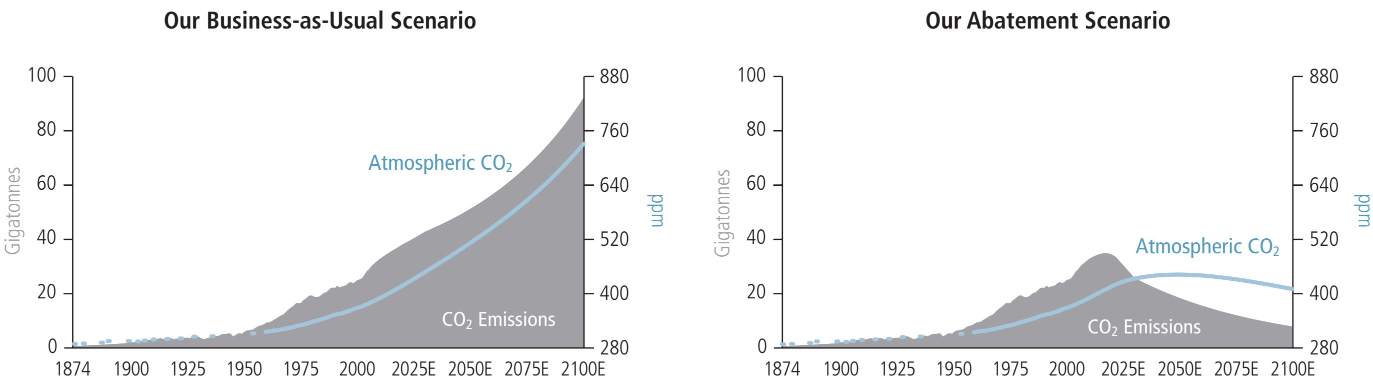
Wealth and Access to Cheap Fossil Fuel Drive per-Capita Emissions



All data are for 2004
Source: World Bank and AllianceBernstein

Display 128

Over the Course of This Century, Abatement Could Make a Huge Difference



Source: CDIAC, EIA, IEA and AllianceBernstein

Nonetheless, under our emissions-abatement scenario in 2030, China and India account for over 36% of global emissions (China alone accounts for 27%). Despite the substantial progress that we expect these countries to make in emissions abatement, they will still have their work cut out for them in the quarter-century beyond our forecast horizon.

Modeling Atmospheric CO_2 Levels

The critical issue with regard to potential climate change is atmospheric concentrations, not annual emissions, of CO_2. To understand how emissions are likely to affect atmospheric concentrations, we had to model CO_2 absorption rates.

Historically, about 40% of man-made CO_2 emissions have been absorbed by the earth and oceans. Ocean absorption of CO_2 has risen in response to higher atmospheric concentrations rather than to higher emissions in any particular year. In essence, if atmospheric concentrations of CO_2 are higher than the equilibrium level for the planet at a particular point in time, the oceans take CO_2 out of the atmosphere, thereby beginning to bring the system back toward balance. This is a slow process. Over the past 100 years, mankind has emitted CO_2 much faster than the oceans could absorb it. If we significantly reduce emissions levels in the next two decades, while atmospheric concentrations remain high, the oceans will begin to absorb an increasing percentage of CO_2 emissions. The oceans will begin to reduce atmospheric concentration of CO_2 once emissions are low enough (beyond our forecast period).

Atmospheric concentrations of CO_2 rose from 321 parts per million (ppm) in 1965 to roughly 380 ppm in 2006. If global CO_2 regulations are not enacted, we estimate that atmospheric concentrations will likely rise to almost 450 ppm by 2030, the lower end of the range that scientists believe could trigger feedback effects leading to an uncontrollably accelerating increase in temperature.

If emissions regulations are never enacted, atmospheric concentrations of CO_2 could climb above 750 ppm by 2100, well past the broad range in which scientists expect feedback effects to kick in (*Display 128, left*). In our emissions-abatement scenario, by contrast, atmospheric concentration levels will likely exceed 430 ppm by 2030, but concentration levels will be rising at a decelerating rate (*Display 128, right*). If emissions continue to fall after 2030, we would expect to see atmospheric concentration levels peak at a little over 440 ppm in 2050 and decline thereafter. ■

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